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Review of British Program on Fluidized-bed Combustion; Report of U. S. Team Visit to England February 17-28, 1969

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Review of British Program on Fluidized-bed Combustion; *Report of U.S. Team Visit to England* February 17-28, 1969

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FOREWORD

This report has been prepared at the request of the National Air Pollution Control Administration (NAPCA) as part of a contractual agreement with the Atomic Energy Commission (AEC) and Argonne National Laboratory. It is based on information obtained during a trip to England.

We are greatly indebted to many British scientists for making available the details of their programs and experimental results, for granting permission to reproduce the figures in this report, and for the many courtesies shown us during our visit.

We are hopeful that the large amount of data, opinions, and general information obtained from our British colleagues are accurately presented and that our interpretations and conclusions based thereon are also accurate. If further details are desired, or if discrepancies appear to exist in certain particulars, we suggest that the original British sources be consulted.

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Review of British Program on Fluidized-bed Combustion; Report of U.S. Team Visit to England February 17-28, 1969

ABSTRACT

A U.S. team visited British organizations that are concerned with the development of fluidized-bed combustion systems for fossil fuels. Information was obtained on research facilities, experimental results, development programs in progress, and expected future work. Experimental efforts and conceptual design studies are aimed at the development of four types of fluidized-bed coal-combustion systems: an atmospheric-pressure utility-sized unit, an industrial shell boiler, a pressurized fluidized-bed combustor, and a packaged water-tube boiler. In addition, application of the technique of fluidized-bed combustion to various fuel-oil burning systems is being studied.

The potential advantages of fluidized-bed combustion over conventional methods of combustion appear to be decreased capital and operating costs; decreased corrosion, erosion, and fouling of steam tubes, capability of burning a wide variety of coals; and the capability of efficiently reducing the emission of atmospheric pollutants at a moderate cost by the addition of a particulate limestone to the fluidized bed.

This report discusses the British experimental results as well as major problem areas requiring resolution for successful development of fluidized-bed combustion.

SUMMARY AND CONCLUSIONS

The British program on fluidized-bed combustion of coal is currently under the direction of the National Coal Board (NCB). The funding level of the program is approximately $2.4 million. The effort consists of experimental studies at the Coal Research Establishment (CRE) and British Coal Utilisation Research Association (BCURA) Industrial Laboratories and design and economic studies by the NCB Research and Development Department. In addition, several boiler manufacturers are conducting, under NCB contracts, conceptual design studies of a variety of commercial and prototype fluidized-bed combustion systems. Four types of systems are under investigation: (a) atmospheric-pressure, utility-sized system, (b) industrial shell boiler, (c) pressurized fluidized-bed combustion system, and (d) packaged water-tube boiler.

The current effort on the development of atmospheric-pressure, utility-sized units involves pilot-plant experimentation at CRE with a newly constructed 3-ft-square fluidized bed and conceptual design studies by Babcock & Wilcox Ltd. of 660- and 120-MW commercial units. The nominal operating conditions for this design involve a superficial gas velocity of 2 ft/sec and coal crushed to minus 1/16 in. The NCB hopes that sufficient information will be available by the end of 1969 for a decision on whether to proceed with the design of a 30-MW prototype unit of this type. According to long-range plans, detailed design of a full-sized power-generating station could hopefully begin in 1971 for operation in the late 1970's. The industrial-shell-boiler development program will involve experimental studies on the prototype unit now under construction at BCURA. The unit is designed to product 8000 lb of steam per hour, which is about equivalent in size to a small industrial unit. The nominal operating conditions are superficial gas velocities of 10-14 ft/sec and coal crushed to minus 1/4 in. The concept of fluidized-bed combustion under pressure offers the possibility of developing an economic system combining gas-turbine and steam-turbine cycles. The program involves experimental work at BCURA using a newly constructed pilot plant capable of burning 1000 lb of coal per hour at 5 atm. Conceptual design studies of a 20-MW prototype and a 120-MW pressurized unit are in progress. The program on industrial water-tube boilers involves a conceptual design study that is underway and experimental studies to be done at a later date. In addition to the NCB program, Esso Ltd. Research Centre has independently investigated combustion (under oxidizing and reducing conditions) and desulfurization of fuel oil in fluidized beds of limestone.

Experimental results in support of the above programs have indicated that a variety of coals can be burned in a fluidized bed of coal ash at about 800°C with superficial gas velocities of 2-14 ft/sec without sintering or agglomeration. The studies involved eight British coals and one American coal. Experiments, mostly in small-scale equipment, have shown that carbon monoxide can be reduced to less than 0.1 vol %, which is equivalent to 0.3% carbon loss. The carbon loss due to elutriation of unburned particles can range from 6 to 25% of the input carbon, depending on the gas velocity and size of coal used as feed. The lower carbon losses were achieved in experiments at low gas velocities (2 ft/sec) and using coal crushed to minus 1/16 in.; the higher losses occurred in experiments at high gas velocities (14 ft/sec) and with coal crushed to minus 1/4 in. Recycling the elutriated material to the bed produced experimental data to indicate that 95% overall efficiency can be achieved for an industrial shell-boiler design and greater than 99% for a conceptual utility-sized fluidized-bed combustor. Heat-transfer coefficients to tubes immersed in the fluidized bed have been found to vary from about 40 to 100 Btu/(hr)(ft^2)(°F), which suggests that the overall size of a boiler could be significantly reduced by using a fluidized-bed combustion concept. The emission of SO_2 into the flue gas has been reduced by as much as 99% at CRE by the addition of $1\frac{1}{3}$ to 2 times the

stoichiometric quantity of limestone along with the coal feed at a superficial gas velocity of 2 ft/sec. Research on nitrogen oxides has suggested that part of the source of this pollutant is the nitrogen compounds present in the coal. Experiments at Esso Ltd. on the combustion and desulfurization of fuel oil in fluidized beds of limestone under both oxidizing and reducing conditions with subsequent regeneration of the limestone suggest the potential applicability of such systems to the combustion of coal as well as oil.

A preliminary cost comparison, made by the British (and converted here to dollars), between utility-sized units and projected to 1975 indicates capital charges of $132/kW for conventional pulverized-coal-feed units, compared with $120/kW for fluidized-bed combustion. If limestone injection were included for both units, the charges would be $137/kW for conventional units and $125/kW for fluidized-bed combustion. Hence, the cost of SO_2 removal is expected to be less than the expected savings in going from conventional firing to fluidized-bed systems. Operating costs, arbitrarily assuming a 50% reduction in SO_2 emissions and burning of 3.5%-sulfur coal, would be 84¢ per ton of coal for a conventional unit, compared with 52¢ per ton of coal for a fluidized-bed unit.

The above experimental and economic studies suggest several potential advantages of fluidized-bed combustion over conventional combustion techniques:

1. Lower capital costs for a boiler because of higher heat-transfer coefficients, which decrease the required tubing area and boiler volume.

2. Decreased corrosion, erosion, and fouling of tubes due to the lower temperature of combustion, which should result in less vaporization of alkali compounds. This may allow less downtime for tube maintenance and may allow operation at higher steam temperatures if desired.

3. Capability for burning a wide range of coals, including those of low quality.

4. Reduction of fuel-preparation costs (crushed coal would be used in fluidized beds), compared with pulverized-fuel firing.

5. Capability for efficiently reducing at a moderate cost the emission of atmospheric pollutants during combustion.

The overall British program in fluidized-bed combustion is aimed at gathering experimental data that would allow the exploitation of some of the apparent advantages of this combustion technique. The development program being pursued by the NCB appears to be a sound, well-planned, well-directed effort. The experimental studies at CRE and BCURA are

comprehensive and are being carried out by capable personnel. However, the program is on a very tight timetable, since the goal is to provide a commercial version of fluidized-bed combustion before nuclear energy becomes too firmly entrenched as a power-generating source; therefore, efforts are aimed chiefly at demonstrating the concept and providing solutions for potential problem areas, rather than at optimization. Pollutant control has not been an important goal of the British program.

The results to date suggest the potential of fluidized-bed combustion and seem to encourage further development of this concept.

Based on discussions with the British, ANL feels that three major problem areas probably require resolution for the successful development of fluidized-bed combustion: coal distribution, air distribution, and recycle of elutriated fines. The first two areas are related to the possible release of carbon monoxide from the fluidized bed, which can lead to system inefficiency as well as corrosion problems. For utility-sized applications, the number of coal feed points required is not known and may have an important effect on economics. Recycle of elutriated fly ash is necessary to achieve the desired overall carbon efficiency for a fluidized-bed system. The total quantity of material that has to be recycled depends upon the gas velocity and the coal size used. For high overall efficiencies, the amount of recycle necessary can approach values raising potential design problems, which may be aggravated if limestone is added to the system to reduce SO_2 emissions.

In addition to the above problem areas, several items appear to warrant further study or consideration:

1. Bed stability--The sensitivity of the design of the system (particularly heat transfer) to changes in the character of the coal feed should be established.

2. Startup and turndown procedures--Feasibility has been established for small-scale experimental equipment, but needs further study for larger-sized equipment.

3. Erosion, corrosion, and fouling--Long-term testing is needed with particular emphasis on high-velocity industrial-boiler concepts and the pressurized fluidized-bed combustion concept.

4. Optimization of operating variables--The interrelated effects of coal particle size, gas velocity, and bed depth need to be analyzed further to determine the overall effect on optimum design and cost of fluidized-bed units.

5. Safety hazards--Hazards peculiar to fluidized-bed combustion should be analyzed.

6. Potential for pollution control--The effects of various limestones and coals and the fluidized-bed parameters of bed height and gas velocity on the reduction of the emissions of SO_2 should be examined. This ultimately should include appraisals of concepts whereby a system to regenerate the limestone additive and recover the sulfur values is used. Means for reducing the emissions of NO_x should be investigated.

7. Future market potential for industrial coal-fired boilers--The potential market for industrial boilers and their relative contribution to the pollution problem should be estimated to determine the priority of industrial boilers in the overall development plan for fluidized-bed combustion.

8. Conceptual designs--Additional conceptual designs are needed that fully exploit the unique potentials of fluidized-bed combustion systems.

I. INTRODUCTION

During February 17-28, 1969, personnel from the National Air Pollution Control Administration and various other organizations visited England to consult with British authorities on the development of fluidized-bed combustion processes. The trip was part of a continuing effort to evaluate the potential of fluidized-bed combustion for contributing to the control of air pollution. Information was obtained on British research facilities, experimental results, the development program, and plans for future work.

The following persons visited England:

National Air Pollution Control Administration, (Division of Process Control Engineering)	- P. W. Spaite, Director, Bureau of Engineering and Physical Sciences
	- P. P. Turner
	- D. B. Henschel
Bituminous Coal Research, Inc.	- E. K. Diehl
Tennessee Valley Authority	- H. L. Falkenberry
Argonne National Laboratory	- A. A. Jonke
	- E. L. Carls

The following organizations were visited:

National Coal Board Headquarters, London
BCURA Industrial Laboratories, Leatherhead, Surrey

Coal Research Establishment, National Coal Board, Stoke Orchard, Cheltenham
Esso Ltd. Research Centre, Abingdon, Berkshire
National Coal Board, Research and Development Department, Harrow, Middlesex

A list of personnel contacted at each organization is presented in the appendix.

II. BACKGROUND

In 1961, a small group at the Marchwood Engineering Laboratories of the Central Electricity Generating Board (CEGB) surveyed the possible uses of fluidization for coal combustion and power generation.[1] The survey indicated the potential advantage of the relatively high heat-transfer properties of fluidized beds in boiler design.

Preliminary studies were made of concepts wherein an inert fluidized bed was used as a secondary heat-transfer medium between very high-temperature (>2700°F) corrosive gases and high-pressure, high-temperature (1200°F) steam tubes. Attempts were also made to absorb the radiant heat from the furnace on the surface of a fluidized bed placed directly below the flame. Results from this early experimentation led to the current concept of combustion of coal in a fluidized bed with heat being transferred directly from the fluidized-bed particles to cooling tubes immersed in the bed. The following are the principal results obtained from small-scale experimentation in an 8-in.-diam vessel and from preliminary design studies.

1. Fouling and corrosion of steam tubes may be reduced because of the lower temperature of fluidized-bed combustion and the resultant lower vapor pressure of alkali-metal constituents of the ash. The workers thought that this fact might allow the use of higher steam temperatures if desired and might offer the possibility of burning a wider range of coals.

2. Although the apparatus did not use recirculation of elutriated fines and overall combustion efficiency could not be determined, ash retained in the bed was burned to below 1% carbon, which is less than that achieved in normal combustion techniques.

3. The overall cost of a fluidized-bed boiler may be substantially less than that of a conventional design, even though the area of a bed of the optimum design appeared at first sight to offer a difficult design problem. The major factor in the expected lower cost for a fluidized-bed boiler is the reduction in tubing requirements. It was estimated that the tube costs for a fluidized-bed utility boiler would be less than $2.40/kW, compared with $7.20 to $9.60/kW for pulverized-fuel boilers.

In 1966 the CEGB decided that it could not carry on the project in view of a very heavy commitment to MHD research, and arrangements were made with the National Coal Board (NCB) to take up the development. The NCB program initially included experimental studies at the Coal Research Establishment (CRE), as well as economic assessments and calculational studies by the NCB Research and Development Department.

In addition to the above, independent research on fluidized-bed combustion of coal was started in 1964 by the British Coal Utilization Research Association (BCURA). In 1969, the name of this organization was changed to BCURA Industrial Laboratories, and after a two-year transitional period, it will be operated as a wholly owned subsidiary of the NCB. Hence, the entire British effort on fluidized-bed combustion of coal is now under the direction of the NCB.

III. STAFFING AND BUDGETS

The NCB and the CEGB are government organizations reporting to the Ministry of Power. A simplified organization chart is shown in Fig. 1

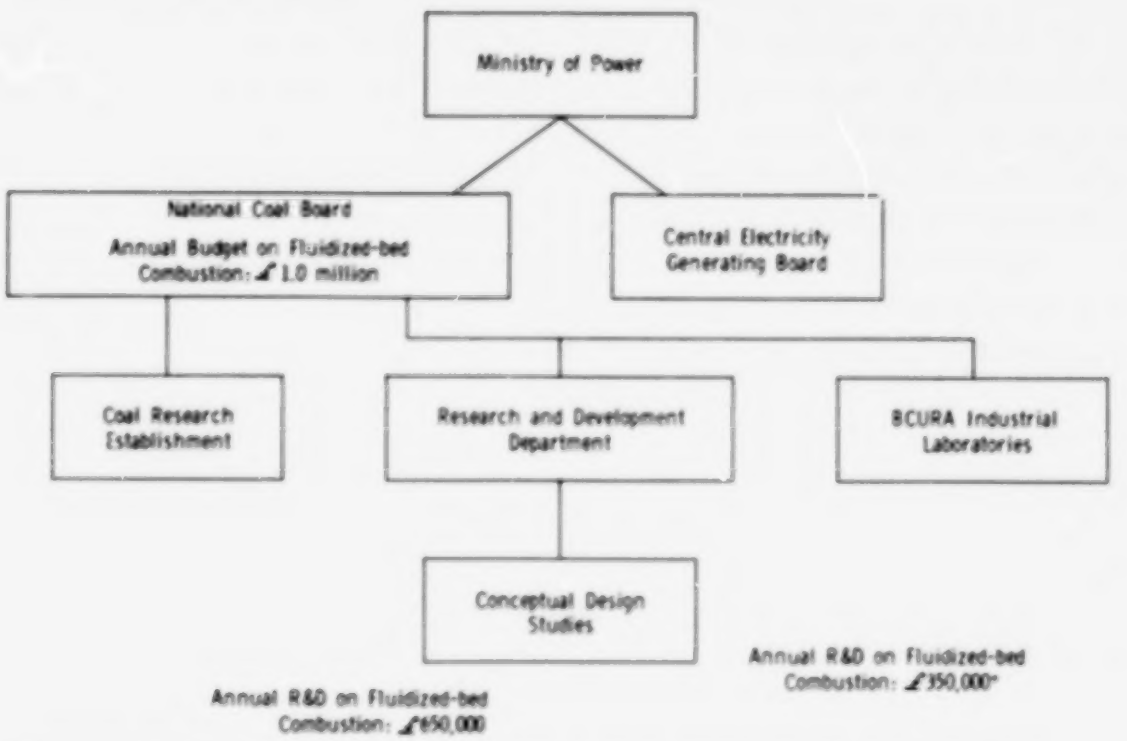

Ministry of Power
National Coal Board
Annual Budget on Fluidized-bed Combustion: £ 1.0 million
Central Electricity Generating Board
Coal Research Establishment
Research and Development Department
BCURA Industrial Laboratories
Conceptual Design Studies
Annual R&D on Fluidized-bed Combustion: £650,000
Annual R&D on Fluidized-bed Combustion: £350,000*
*Of this, approximately 60% is associated with the development of industrial shell boilers, and 40% is directed toward pressurized fluidized-bed combustion.

Fig. 1. Organizational Chart of British Effort on Fluidized-bed Combustion

The NCB employs 300,000-400,000 persons and operates 300-400 mines. The annual budget is over $2 billion (£900 million), with an expenditure of $11 million (£4.5 million) on all areas of research and development. Approximately $4.8 million (£2.0 million) of this amount is allocated for

research on coal products and combustion, and $2.4 million (£1.0 million) is allocated for research and development on fluidized-bed combustion. The research and development effort consists of experimental studies at CRE and BCURA, as well as economic and conceptual design studies.

The CRE employs 350 persons, of whom 100 are scientist and engineers. Of these, 8 staff personnel and 14 assistants work on fluidized-bed combustion. The total annual budget is $2.4 million (£1.0 million). The annual expenditure on fluidized-bed combustion experimental studies at CRE was not obtained, but the combined annual expenditure at CRE for fluidized-bed experimental studies and conceptual design studies appears to be $1.5 million (£650,000). The cost of the new pilot-plant facility at CRE was quoted as being between $450,000 and $600,000 (£180,000 and £250,000). Although no total figure for conceptual design studies was obtained, it was stated that the NCB voted on February 7, 1969, to allocate $240,000 (£100,000) for additional design studies.

BCURA Industrial Laboratories employ approximately 250 persons, of whom 150 are technical. Of the latter, about 50% are college graduates. The total annual budget is about $1.4 million (£600,000). Of this, approximately $850,000 (£350,000) is furnished by the NCB, with the remainder obtained as Deficiency Grants from the Ministry of Technology. The annual budget for fluidized-bed combustion work at BCURA is approximately $840,000 (£350,000). Of this, approximately 60% is devoted to development of an industrial shell boiler and 40% to investigation of fluidized-bed combustion under pressure. The total estimated cost to date for industrial shell boiler development, including the design and installation of a new 8000-lb steam/hr unit, is $960,000 (£400,000).

IV. OVERALL PROGRAM

The overall goal of the NCB fluidized-bed combustion program is to promote the continuing use of coal as an energy source for both large-sized electrical power-generating units and industrial steam boilers. Although, at present, coal-fired stations supply 77% of England's electricity,[2] the CEGB has committed itself heavily to nuclear energy, and new coal-fired electrical generating stations will probably not be built unless improved combustion methods, such as fluidized-bed combustion, are developed. The other area of main interest in fluidized-bed combustion appears to be packaged boilers for industrial steam raising. This field is now dominated by oil, principally because of the higher capital costs of small coal-fired units.

The current NCB program involves experimental studies at CRE and BCURA Industrial Laboratories, as well as assessments by the NCB Research and Development Department. In addition, the NCB has contracted

with boiler manufacturers to provide several conceptual design studies to point out areas where additional information is needed for future detailed design studies and, hopefully, prototype construction.

Four types of fluidized-bed combustion systems are under investigation: (a) atmospheric-pressure utility-sized system, (b) industrial shell boiler, (c) pressurized fluidized-bed combustion system, and (d) packaged water-tube boiler. In addition, the application of fluidized-bed combustion to the superheater section of existing utility boilers is being considered as a means of prolonging the life of coal-fired stations.

A. Atmospheric-pressure, Utility-sized System

The experimental program associated with the design of an atmospheric-pressure, utility-sized, fluidized-bed combustion system is being carried out at CRE. High overall combustion efficiency is a principal goal, and high heat-transfer coefficients are sought to reduce the number of boiler tubes, which account for a large fraction of the cost of a utility-sized generating unit. The chosen nominal operating conditions include a superficial fluidizing-gas velocity of 2 ft/sec and coal crushed to minus 1/16 in. Most of the past experimental data have been obtained with a 6-in.-diam fluidized-bed combustor. A pilot-plant unit having a 3 by 3-ft cross-sectional fluidized bed has recently been constructed and is in operation. It is hoped that data from this unit, augmented by support studies from several smaller test units and larger mockup rigs, would provide sufficient design data to scale up to a prototype unit. Babcock & Wilcox Ltd. has a contract with the NCB to do conceptual design studies of 660- and 120 MW units of this type. The 660-MW study has been going on for 5-6 months and was expected to be completed by April 1969. The NCB also hopes to have sufficient information by the middle to the end of 1969 to make a decision on whether to proceed with a 30-MW prototype unit. The NCB had been negotiating with the National Research Development Corporation (a government organization whose purpose is to develop inventions in the public interest) to finance a prototype installation, probably feeding the national grid. They expect such a unit to have a 20 by 30-ft cross section and to cost between $4.8 million (£2 million) and $7.2 million (£3 million). The tentative schedule, as envisioned by NCB, would be to start construction in 1970 and have the prototype operational in 1971. Upon successful demonstration of the prototype and with CEGB approval and support, NCB plans call for detailed design of a large power generating station in 1971-1972, with operation in the late 1970's.

B. Industrial Shell Boilers

The experimental program on industrial shell boilers is being carried out at BCURA Industrial Laboratories. The purpose of the work has

been to develop a new and cheaper coal-fired packaged shell boiler to compete with oil-fired units at capacities up to 50,000 lb of steam per hour. Coal-fired units of conventional design are limited to about 35,000 lb of steam per hour and have capital costs about 30% higher than oil-fired units. Because of this goal of reduced size and lower capital costs, experimental conditions are focused on high heat-release rates per unit volume. The nominal operating conditions used are superficial fluidizing-gas velocities of 10-14 ft/sec and coal crushed to minus 1/4 in.

A 2-ft-diam pilot-plant facility, capable of burning up to 500 lb of coal per hour, was used to obtain most of the past experimental data. A prototype unit (3-ft diameter, 1000 lb of coal per hour) has been designed and fabricated in collaboration with John Thompson Ltd. (Shell Boiler Division). BCURA hoped to have this unit operational by the end of May 1969. The capacity of this prototype is 8000 lb of steam per hour, which is in the lower part of the range of the capacity of shell boilers, but sufficient to supply the steam and heating requirements of the BCURA site.

The intention is to obtain sufficient experience with the prototype plant boiler by the autumn of 1969 to enable the first commercial industrial unit (30,000 lb of steam per hour) to be designed. It is believed that the design will be capable of scale-up to 50,000 lb of steam per hour, i.e., in excess of conventional coal-fired units and up to the limit of oil-fired units. BCURA hopes that the marketing department of the NCB will find industrial concerns that are in the market for a new boiler and are willing to experiment with the industrial-sized unit under a NCB subsidy. If detailed design is started this autumn, it is expected that the unit could be operational in 18 months, i.e., 1971.

C. Pressurized Fluidized-bed Combustion System

BCURA is investigating the principle of carrying out fluidized-bed combustion under pressure. Here the combustion principle offers the possibility of developing an economic, combined gas-turbine and steam-turbine cycle for power generation. This application, where the aim is higher overall thermal efficiency and substantially lower capital costs of a power station, depends on being able to run a gas turbine with the pressurized combustion products. Whereas past attempts to develop a coal-fired gas turbine have failed, because of the deposition of mineral matter and ash erosion of the turbine blades, the character of material carried over to the turbine from fluidized-bed combustion should differ sufficiently to avoid this problem.

An experimental apparatus has been constructed at BCURA to burn 1000 lb of coal per hour at 5 atm. The unit has a 4 by 2-ft cross section. Initial testing began in the latter part of February 1969. In addition to the

combustor, a full-scale model operating at atmospheric pressure is also being built. A group consisting of CEGB, John Thompson Ltd., and turbine manufacturers (through Professor Elliot, BCURA consultant) has been formed to provide an initial assessment of the feasibility of the process and the economic benefit that might accrue from it. It was hoped that this assessment would be available by June 1969 and that a more detailed assessment and proposals for the next stage of development would be available by the latter part of 1969. NCB also mentioned that John Thompson Ltd. is working on conceptual designs for a 20-MW prototype and a 120-MW pressurized unit.

D. Industrial Water-tube Boilers

The NCB has a contract with Preece, Cardew and Rider (consulting firm in Brighton, Sussex) for conceptual design studies of packaged water-tube boilers. The firm is working on a unit designed to produce 50,000-200,000 lb of steam per hour and will study units up to 120 MW. A preliminary costing has been made, and the direction the program will take will be decided within a few months. The design conditions call for superficial fluidizing-gas velocities of 8 ft/sec and coal crushed to minus 1/8 in. Both CRE and BCURA expressed interest and have the capabilities to do supporting experimental work, but no firm plans appear to have been made.

E. Summary of Status of Conceptual Design Studies

The status of the conceptual studies is summarized in Table I.

TABLE I. Status of Design Studies

Type of Unit	Size	Contractor	Type of Study	Status
CRE atmospheric utility size	660 MW	Babcock & Wilcox Ltd.	Conceptual design	Due April-May 1969; have worked on 5-6 months.
CRE atmospheric utility size	120 MW	Babcock & Wilcox Ltd.	Conceptual design	-
CRE atmospheric utility size	20-30 MW	Babcock & Wilcox Ltd.	Prototype	To decide in the middle to end of 1969 whether to proceed with detailed design. If yes, construct in 1970 for operation in 1971.
BCURA shell boiler	8,000 lb of steam per hour	John Thompson Ltd.	Prototype	Being fabricated; expected by April 1969.
BCURA shell boiler	25-30,000 lb of steam per hour	John Thompson Ltd.	Industrial size	Decision by autumn 1969; 18-month construction, operational in 1971.
BCURA pressurized	120 MW	John Thompson Ltd.[a]	Conceptual design	Preliminary assessment by middle 1969; detailed assessment by end 1969.
BCURA pressurized	20 MW	John Thompson Ltd.[a]	Prototype	Under study.
Packaged water tube	50,000-200,000 lb of steam per hour	Preece, Cardew and Rider Ltd.	Conceptual design	In progress; decision in next few months on future work.
Packaged water tube	120 MW	Preece, Cardew and Rider Ltd.	Conceptual design	Will do.

[a]Working party with CEGB, BCURA, and turbine manufacturers.

F. Miscellaneous

Both CRE and BCURA have done preliminary studies of the effect of limestone injection on the reduction of SO_2 emissions during fluidized-bed combustion. At present there are no firm plans to continue this work.

The NCB has stated that the West European Coal Producers Association (Germany, France, Holland, and Belgium) is interested in fluidized-bed combustion and hopefully may be a source of additional funds. The German interest stems in part from the antipollution potential of fluidized-bed combustion. The negative French attitude in the past was probably due to unusual conditions in the French coal industry, i.e., high government subsidies.

Independent research on the desulfurization of fuel oil in fluidized beds of limestone is being done at Esso Ltd. Research Centre. The reactions occurring under both oxidizing and reducing conditions are being studied, as well as the regeneration of the sulfated limestone and recovery of sulfur values. Certain aspects of the work may be applicable as well to pollution control during the fluidized-bed combustion of coal.

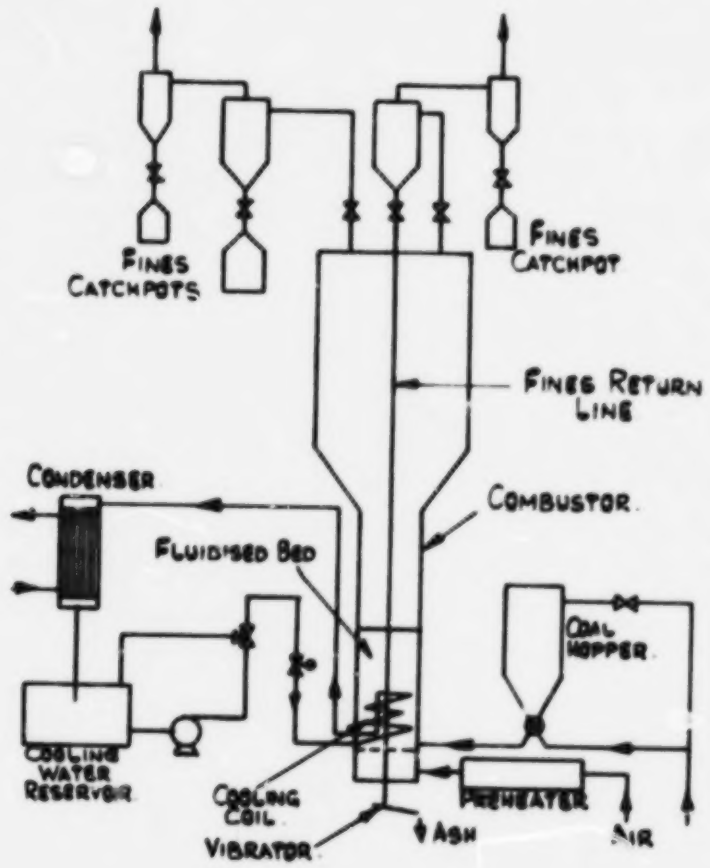


Fig. 2. Six-inch (0.156-m) Fluidized-bed Combustion Plant (Coal Research Establishment[6])

V. SUMMARIES OF PREVIOUS EXPERIMENTAL WORK

A. Coal Research Establishment[3-7]

Most of the experimental data on fluidized-bed combustion was obtained using a 6-in.-diam stainless steel combustor. Figure 2 is a schematic diagram of the equipment used. The air distributor was a perforated plate with forty-five 2.4-mm-diam holes covered with three layers of 10-mm refractory pebbles. Coal, crushed to minus 10 BSS mesh (minus 1/16 in.), was fed at 400-800 g/hr through a rotary valve and pneumatically injected into the fluidized bed. The heat produced by combustion was removed by a water coil in the bed. Bed height was determined by pressure probes and automatically maintained constant by running off surplus ash through the base. The gas leaving the combustor was dedusted by two cyclones in series, with the capability for recycling the primary cyclone fines, via an internal dip leg, back to the bed if desired.

Initial experiments were performed with unwashed Babbington coal of 25% ash content at bed temperatures of 700-800°C (1212-1472°F), superficial fluidizing velocities of 1, 2, and 3 ft/sec, bed heights of 16 to 40 in., and up to 30% excess air. The fluidizing velocities were chosen to achieve high heat outputs without excessive elutriation from the bed. In the experiments at 1 ft/sec, the maximum coal particle size was reduced to 30 BSS (minus 1/64 in.) to ensure that all particles were fluidized. Runs were carried out for periods of 4-30 hr. Subsequent tests were conducted at 800°C and a fluidizing velocity of 2 ft/sec with two other coals: Goldthorpe (17% ash content) and an American coal of high swelling property, Farmington* (10% ash content).

The main conclusions drawn from the tests are the following.

1. No difficulty was found in maintaining stable conditions in the combustor, even when the highly coking Farmington coal was burned. No agglomeration of the low-fusion-point ashes (initial deformation point: 1100°C) from Farmington and Goldthorpe coals was observed during combustion tests at 800°C.

2. No tar was detected in any part of the system, and the only combustible gas present above the bed was carbon monoxide. At 800°C and 20% excess air, the amount of carbon monoxide leaving the bed was small. At 700°C, however, loss of carbon monoxide was appreciable. At both temperatures, an increase in fluidizing velocity increased the carbon monoxide concentration in the off-gas. Its concentration at 700°C, 20% excess air, and a superficial fluidizing velocity of 2 ft/sec was 0.7 vol %, and under similar conditions at 800°C, the concentration was less than 0.1 vol %.

3. Loss of unburnt carbon from the bed occurred almost entirely by elutriation. The loss was reduced from 6.5% of carbon throughput to 0.15% by recycling the primary cyclone fines back to the bed. Thus, at 800°C and fluidizing at 2 ft/sec with fines recycle, the total combustibles loss was equivalent to only 0.5% carbon. When the proportion of excess air was reduced to less than 20%, the loss of combustibles did not increase markedly until stoichiometric conditions were reached; the CO concentration then increased to 1.4 vol %. Neither varying the bed height between 1 and 3 ft nor changing from low-rank coal to a coking coal affected the loss of CO and carbon.

4. The main ash product was a porous, nonfused sand containing less than 0.1 wt % carbon. Its fluidized density was 35 lb/ft^3. Little degradation of the ash took place during fluidization. Both English coals formed ash beds of similar size distribution and density, and bed height was readily

*Mountaineer Coal Company Division, Consolidation Coal Company, Mine 9, Farmington, W. Va.

maintained because only 15% of the ash was carried through the recycle cyclone. The American coal, however, did not form a bed of its own since all the ash was elutriated.

Heat-transfer coefficients were measured in a 1-ft-square combustor, with a horizontal tube immersed in a bed of minus-1/16-in. particles. Coefficients between 80 and 100 Btu/(hr)(ft^2)(°F) were measured, depending upon whether the tube was cooled with water or air. These results agree well with predictions made from literature data. Using a 3-ft-square unit, heat-transfer coefficients were measured between a fluidized bed of ash and 1¼-in.-OD tubes arranged horizontally in a triangular pattern. Hot water was passed through the tubes, and the bed was fluidized with cold air. The results showed that increasing and fluidizing velocity from 2 to 4 ft/sec increased the coefficient by 10%, and increasing the tube spacing from 2.5 to 10 in. increased the coefficient by 25%. Higher coefficients were obtained when the tube bundle was near the top of the bed. Changing the maximum particle size from minus 1/16 in. to minus 1/8 in. and recycling fines to the bed did not affect the coefficient significantly.

Elutriation experiments have been carried out in cold beds of ash using a 1-ft-square unit. The elutriation rate of particles was determined by two methods:

1. Measuring the recycle rate under steady conditions (recycle method).

2. Measuring incremental carryover rates as fines are blown from a bed having an initially high concentration of fines (elutriation method).

The mean residence time of the fines per cycle, in a bed fluidized at 2 ft/sec, was between 1 and 4 min.

Information has been obtained, with radioactive tracers and a 5-ft-diam cold unit, on the rate at which particles move laterally through a fluidized bed.

B. BCURA Industrial Laboratories[8-14]

From a survey[8] of the literature in 1964, BCURA concluded that it should be feasible to develop a packaged shell boiler in which coal is burned in a bed of fluidized coal ash (approximately 98% of the bed being ash) with cooling tubes immersed in the bed. Preliminary experiments[9,10] on small combustion pots confirmed the possibility of such a system and, in particular, showed that combustion could be almost completed (except for carbon in carryover) within the bed volume, under conditions that kept the bed at 800-900°C, i.e., sufficiently low that the ash particles would not sinter.

A pilot-plant-scale (27-in.-diam) mild-steel combustor was commissioned in July 1966 to pursue this investigation. Figure 3 is a schematic diagram of the apparatus. The unit was designed to operate with a combustion rate of 300-400 lb of coal per hour, excess air up to 20%, a mean bed temperature of 870°C, and a maximum heat release rate of 10^6 Btu/hr per square foot of cross-sectional area. From these specifications it followed that the maximum superficial velocity would be 10-15 ft/sec. The air distributor was a bubble-cap design using 1/2-in. caps with ten 1/8-in. holes around their circumference. A total free area of 4.5% was used for the distributor. The gases leaving the unit were passed through a high-efficiency cyclone, which was theoretically capable of capturing 10-μm particles. Recycle of material from the cyclone back to the unit was provided for via a rotary feeder and pneumatic injection with the coal feed.

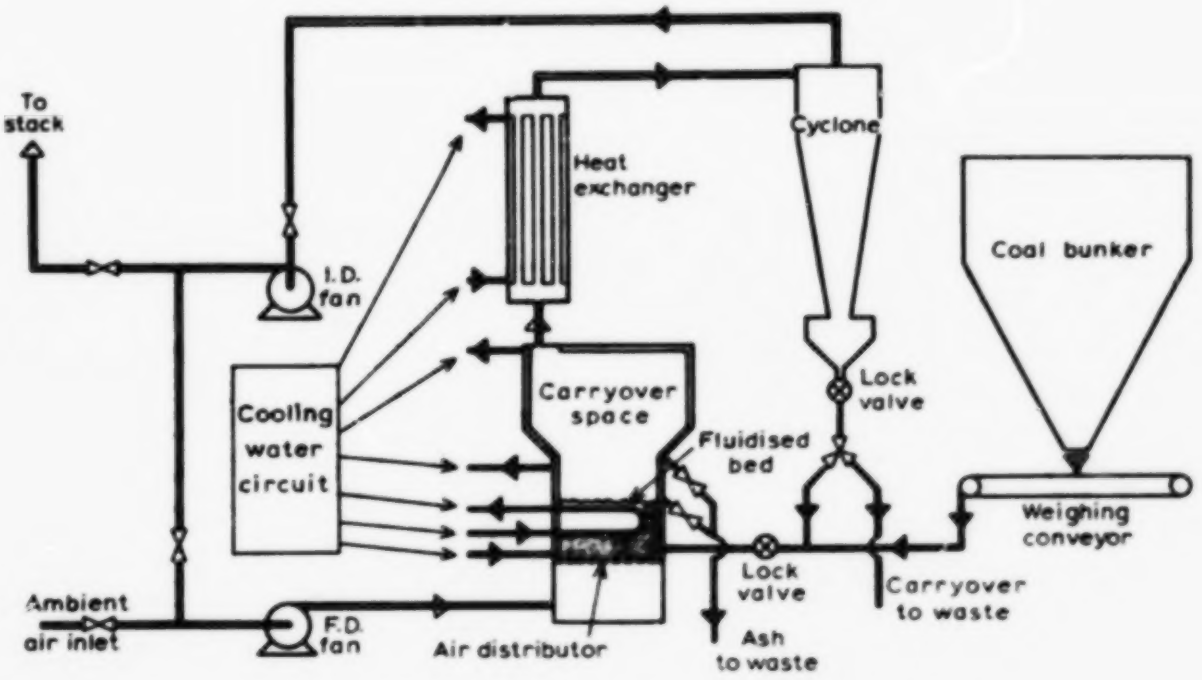


Fig. 3. Diagrammatic Layout of Pilot-scale Fluidized-bed Combustion System (BCURA Industrial Laboratories[12])

Because of the desirability for large heat-release rates, which necessitates high superficial velocities, the coal particles used must be large enough so that a significant fraction is not elutriated out of the bed before combustion occurs. Six different coals were tested, one washed and the rest untreated. Tests were made with minus-1/8-in. and minus-1/4-in. coal. Superficial velocities ranged from 7 to 14 ft/sec.

The main results of the tests are as follows:

1. When untreated coal was burned, the shale in the coal supply was more than adequate to replace losses due to attrition, and bed depth could be maintained by continuous drainage over a weir. However, for washed coal, insufficient ash was added with the coal to counteract the loss of bed material that was elutriated due to attrition.

2. The carbon monoxide content of the flue gases 2 ft above the bed was about 1 vol % with stoichiometric air, it fell below 0.5 vol % with 20% excess air, and below 0.2 vol % with greater than 50% excess air. The CO level appeared unaffected by the combustion rate, and vertical transverses approaching the bed surface detected only slight changes in flue-gas composition, suggesting that only a small proportion of the heat release was occurring above the bed. The bed depths used were between $1\frac{1}{2}$ and 2 ft. The heat lost from the combuster in the form of CO increased with decreasing bed heights.

3. Calculations indicated that the carbon content of the bed was less than 5 wt %. The mean bed temperature was controlled between 870 and 900°C, above which the bed was liable to sinter.

4. The major heat loss from the fluidized bed was due to unburned, elutriated carbon. If none of the solids trapped by the cyclone were recycled to the combustion bed, then the heat loss as elutriated carbon could be as high as 25% of the heat supplied. However, when between 50 and 80% of the solids were recycled, such losses were substantially reduced. At 50% recycle and 14 ft/sec, the carbon loss could be reduced to 10% of the heat input. Higher recycle rates could not be accommodated with the experimental unit because of the cooling effect the recycled solids had on the bed. Chemical analysis of the elutriated solids and calculations indicated that if all elutriated solids sized greater than 76 μm were recycled to the combustor, with smaller particles being caught by a secondary collector, then the carbon loss due to elutriated solids could be reduced to 4-5%.

5. Heat-transfer coefficients between 35 and 50 Btu/(hr)(ft^2)(°F) were attained both at the walls and for tubes immersed within the bed. In the 2-ft-deep bed with internal tubes, the heat-transfer rate at the walls was uniform throughout the depth of the bed and independent of the fluidizing velocity. Without tubes in the bed, the bed-to-wall heat-transfer rate at low fluidizing velocities was low near the air distributor, and increased to a value similar to that with tubes at the top of the bed. As the fluidizing velocity was increased, the heat-transfer rate in the top half remained constant while that in the bottom half increased. This behavior was thought to be due to the segregation and defluidization of large particles at low velocities in the absence of tubes.

The bed-to-tube heat-transfer rates were independent of the fluidizing velocity, except immediately above the air distributor.

6. With fluidizing velocities in the range of 7-14 ft/sec, heat-release rates of 400,000 to 1,200,000 Btu/(hr)(ft^2) of distributor area were obtained by using 0-90% excess air.

C. Retention of Sulfur Compounds and Behavior of Nitrogen Oxides

1. Coal Research Establishment[15,16]

Measurements have been made, during the combustion of coal in the 6-in.-diam fluidized bed, of (1) the emission of sulfur as sulfur dioxide and trioxide and (2) its retention as sulfate in the ash, secondary cyclone fines, and dust. The combustion conditions in these runs were 800°C, 2-ft/sec fluidizing velocity, 2-ft bed height, 10-20% excess air, and primary cyclone fines recycled to the bed. Varying quantities of limestone were added with the coal feed.

The amount of sulfur retained depended not only on the amount of limestone that was added, but also on the inherent CaO present in the coal ash. Addition of 12 wt % minus 10 BSS limestone to Goldthorpe Coal (total CaO about twice the stoichiometric quantity) led to the retention of virtually all the sulfur, with about 10 ppm remaining in the off-gas. On addition of a similar proportion of limestone to Farmington Coal, 80% of the sulfur was retained. Crushing the limestone feed to minus 120 BSS mesh to expose a greater area resulted in the retention of 99% of the sulfur on addition of only $1\frac{1}{3}$ of the stoichiometric amount. The data are plotted in Fig. 4.

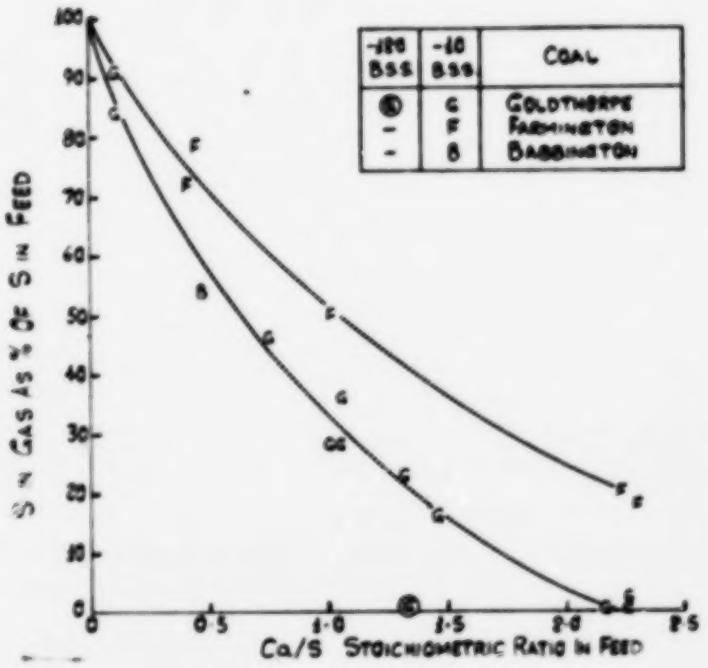


Fig. 4. Sulfur Retention by Limestone (Coal Research Establishment[16])

Following the addition of limestone, the sulfur content of the off-gas reached its new equilibrium level much more rapidly than the free lime content of the bed, which continued to increase for several hours. The total length of each run was about 10-12 hr. Comparison of the data from different runs also indicated that the proportion of free lime in the bed did not affect the sulfur content of the gas. This suggested that most of the lime lay in the interior of each particle and was not readily accessible. The sulfur in the ash was entirely sulfate with no sulfite. The reason for the different results with the Goldthorpe and Farmington coals is not known. Little decrepitation of the limestone seemed to occur, and the amount of fly ash passing through the recycle cyclone was not greatly increased by adding limestone.

Without the addition of limestone, the chlorine content of the coal was not retained in the ash, but was evolved in the flue gas, apparently

as hydrogen chloride. Only a small proportion of the chlorine was retained when sufficient limestone was added to retain most of the sulfur.

No measurements of nitrogen oxides have been made.

2. BCURA Industrial Laboratories[17,18]

BCURA has used the 27-in.-diam pilot-plant unit to test the effect of adding limestone with the coal feed to reduce emissions of SO_2. The tests were run at 1600 ± 30°F, 20-30% excess air, and 12-ft/sec superficial velocity. The washed coal used contained 8% ash. Since the ash associated with this coal was elutriated under these conditions, an inert bed of refractory grog was used as the fluidized medium. The tests were conducted for 6-7 hr; Table II shows the conditions during the last 2 hr of each run.

TABLE II. Experiments on Sulfur Capture by Adding Limestone (BCURA Industrial Laboratories[17])

Type of Additive	Stoichiometric Addition Rate of CaO	SO_2 in Flue Gas, ppm	Percentage of Sulfur Retained in Bed
No additive	-	930	5-10
1/4-in. chips	1	700	30
1/4-in. chips	2	560	44
Crushed material, 1/4-1/32 in.	1	730	27
Crushed material, 1/4-1/32 in.	2	530	47
120 mesh (CRE type limestone)	2	350	65

The results indicated that no improvement in SO_2 capture was obtained by crushing the chips of limestone to 1/4-1/32 in. The better SO_2 capture for the last test could have resulted from the finer size of material or the fact that the limestone (obtained from CRE) was a more reactive material than the limestone used in the first BCURA tests. The sulfur balances were about 80% for the tests. Approximately 20-50 ppm of SO_3 was present in the flue gas.

Oxides of nitrogen were measured during one experiment. At 18% excess air and a mean bed temperature of 880°C, 400-450 ppm of NO were measured at the cyclone inlet.

Additional work at BCURA[19] involved a comparison of five different methods for analysis of oxides of nitrogen and showed that the NO content of the flue gas from a high-intensity coal combustor operating at 2570°K was over 1 vol %, approximating the value predicted by thermodynamics. Experiments were also done on the combustion of carbon monoxide at temperatures below 1170°K (900°C) in various atmospheres and in the presence of various concentrations of volatile organic nitrogenous additives of three types. Fixation of atmospheric nitrogen took place to a very small extent, as would be expected from considerations of thermodynamic equilibrium, but when 1-2% of any of the nitrogenous additives were present in the fuel with a small excess of oxygen, the concentration of oxides of nitrogen in the exit gas rose to over 1000 ppm; these values are much greater than thermodynamic equilibrium values for the N_2-O_2 reaction. A striking feature of the results was that when insufficient oxygen was present for complete combustion, the effect of increasing the concentration of additive beyond a certain point was to produce a fall--in certain conditions a substantial one--in the concentration of oxides of nitrogen determined in the exit gas. With secondary butylamine as the additive, such a fall took place even when a small excess of oxygen was present. The chemical nature of the bonding of the nitrogen in the additive is therefore important. When coal was introduced into the flame, the increase in NO level accounted for 50% conversion of the nitrogen content of the fuel to NO. The results suggest that a significant fraction of the NO in the flue gas at relatively low flame temperatures may be caused by nitrogen compounds in the fuel and also that emissions of oxides of nitrogen during fluidized-bed combustion may even be reduced by introducing a nitrogen-containing additive to the fuel.

Additional tests[20] have suggested that fixation of atmospheric nitrogen may be catalyzed by nitrogen compounds in the fuel.

Another theory is that unstable nitrogen oxide compounds are preserved at higher than equilibrium values for NO due to the kinetics of a series of chemical reactions and rapid quenching, which prevents attainment of final equilibrium values.

D. Esso Ltd. Research Centre[21]

Esso Ltd. Research Centre investigated the combustion of fuel oils in fluidized beds of limestone and the resultant capture of sulfur compounds by the bed material. The limestone reacted with the sulfur compounds when combustion was carried out under oxidizing conditions and also if partially reducing conditions were employed. In the former case, the reaction product is $CaSO_4$; under the latter conditions, CaS is formed. The regeneration of both of the above reaction products to yield SO_2 and CaO was also studied. The reactions are summarized in Fig. 5.

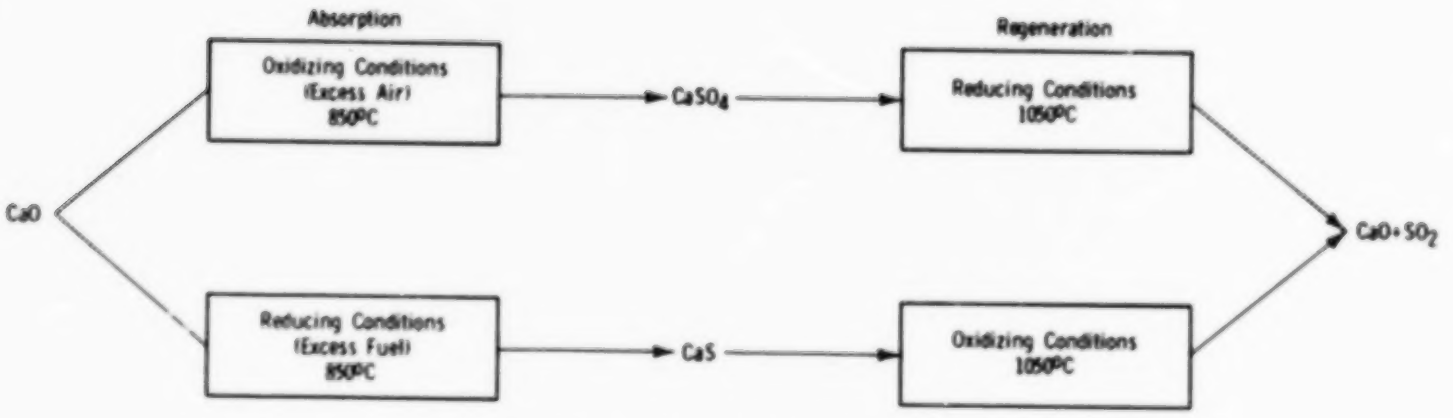


Fig. 5. Reaction Products Formed during Fluidized-bed Desulfurization of Fuel Oil (Esso Ltd. Research Centre[21])

The experimental equipment used for the above studies was a mild-steel, refractory-lined, 7-in.-ID vessel. Fuel was injected into the fluidized bed, about 3 in. above the refractory air distributor, through $3\frac{1}{4}$-in.-ID tubes, each having an air-cooled annulus. A steam coil immersed in the bed was used for temperature control. Gas velocities of 1-2 ft/sec were used with limestone particles of 600-1200 μm and bed depths of 12-15 in. No cyclone or alternative gas-cleaning device was used during these experiments.

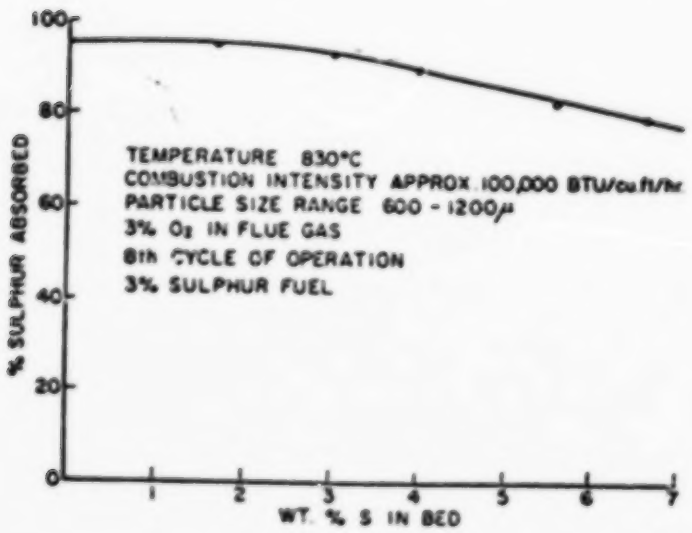


Fig. 6. Desulfurizing Combustion of Fuel Oil--Effect of Sulfur Content of Bed on Sulfur Oxide Absorption (Esso Ltd. Research Centre[21])

A summary of the experimental results is presented below:

1. <u>Sulfur Absorption under Oxidizing Conditions</u>

Figure 6 shows the effect of sulfur content of the bed on efficiency of sulfur capture under oxidizing conditions. These data were obtained at 830°C with 3% oxygen in the flue gas. The data indicate high efficiency for sulfur capture at up to 7 wt % sulfur in the bed.

Figure 7 shows the effect of temperature on sulfur capture at one level of bed conversion (31% of bed reacted). The data show a maximum at about 875°C. As conversion of the stone increases, the O_2/SO_2 molar ratio must be increased to effect similar SO_2 removals, as shown in Fig. 8. Data for these two figures were obtained using an external source of flue gas and an electrically heated fluidized bed of 100- to 200-μm limestone particles.

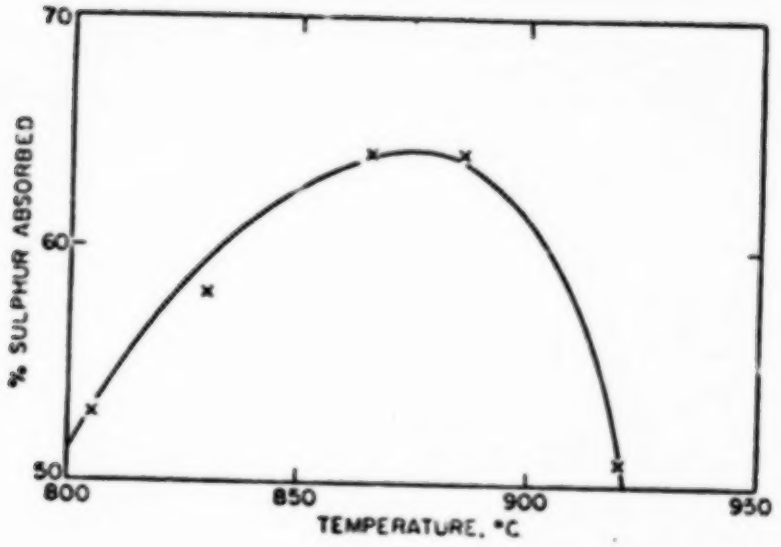


Fig. 7. Optimum Temperature for Sulfur Oxide Absorption by Lime (31% of bed reacted) (Esso Ltd. Research Centre[22])

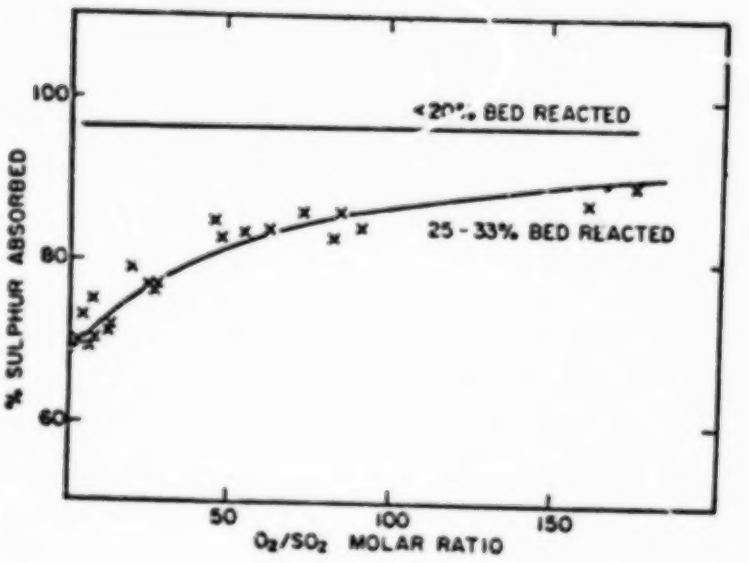


Fig. 8. Sulfur Oxide Absorption by Lime at 865°C (Esso Ltd. Research Centre[22])

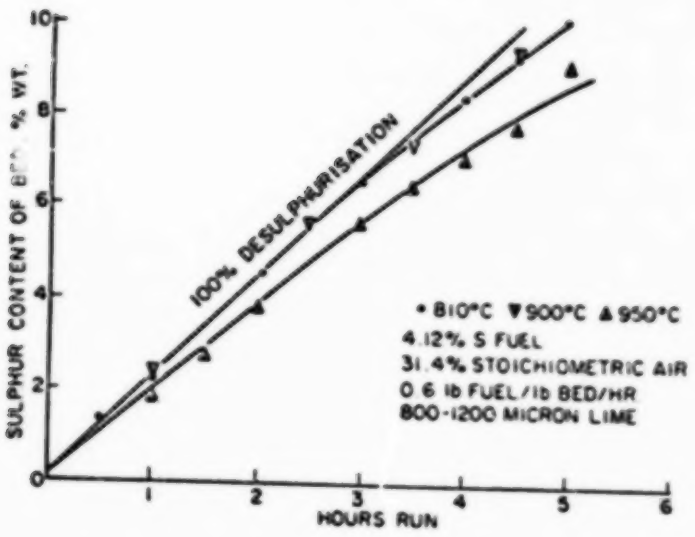


Fig. 9. Desulfurizing Gasification; Temperature Effect (Esso Ltd. Research Centre[21])

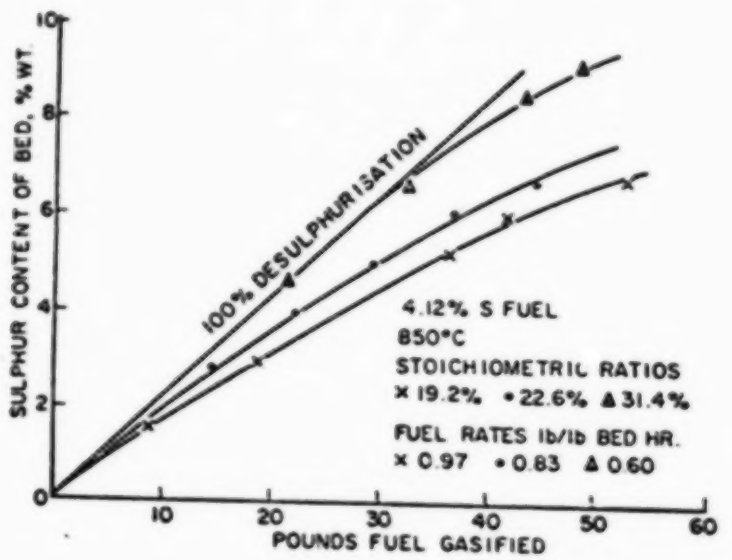
2. Sulfur Absorption under Reducing Conditions

Figure 9 shows the effect of temperature upon the absorption of sulfur under reducing conditions. The data indicate that at 31.4% of stoichiometric air, and with a 4.12%-sulfur fuel, efficient absorption of sulfur occurs when the bed contains up to 6 wt % sulfur over the range 810-900°C. At 950°C, the absorption efficiency drops.

Figure 10 shows the effect of the degree of reducing conditions upon sulfur capture. A drop in efficiency was noted for more strongly reducing conditions than 30% of stoichiometric, although this effect may be confounded with that of fuel rate since the airflow was held constant.

Fig. 10

Desulfurizing Gasification; Effect of Stoichiometric Ratio (Esso Ltd. Research Centre[21])



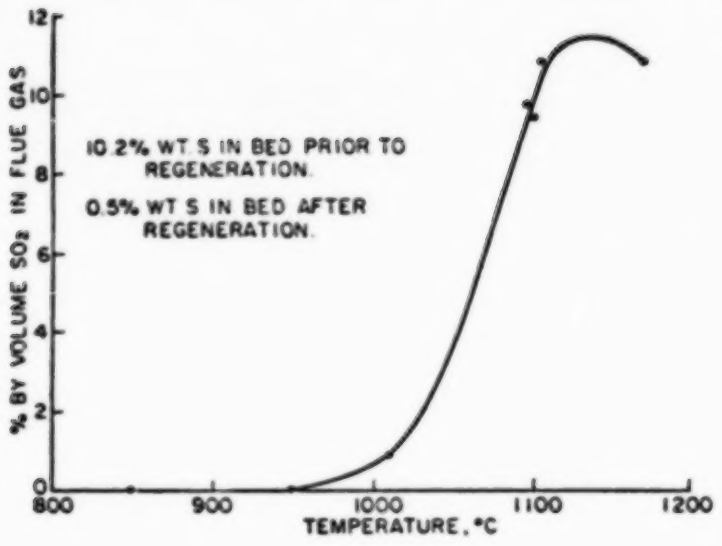


Fig. 11. Air Regeneration of Sulfided Bed (Esso Ltd. Research Centre[21])

The regeneration of the sulfided beds was accomplished by shutting off the fuel and leaving the air on. This resulted in a rapid rise in both the temperature and the SO_2 content of the flue gas, as seen in Fig. 11. About 95% of the absorbed sulfur was removed.

Esso Ltd. has several different possible applications in mind, based on their experimental data. The first involves a continuous fluidized-bed lime kiln together with recovery of sulfur values from the fuel oil.

Figure 12 shows a concept involving the conversion of a conventional boiler to a gasifier with desulfurizing operation. In effect, a desulfurizing gasifier is built into the bottom of the furnace, temperature being controlled partially by heat transfer to the water walls and partially by varying the stoichiometric ratio. A multiplicity of refractory cyclones serves also as a gas burner, the secondary air being used to cool the roof structure of the gasifier. There would also be an external regenerator and means for reducing the concentrated SO_2 to elemental sulfur. Alternatively, the small-volume stream of concentrated SO_2 could be neutralized and disposed of.

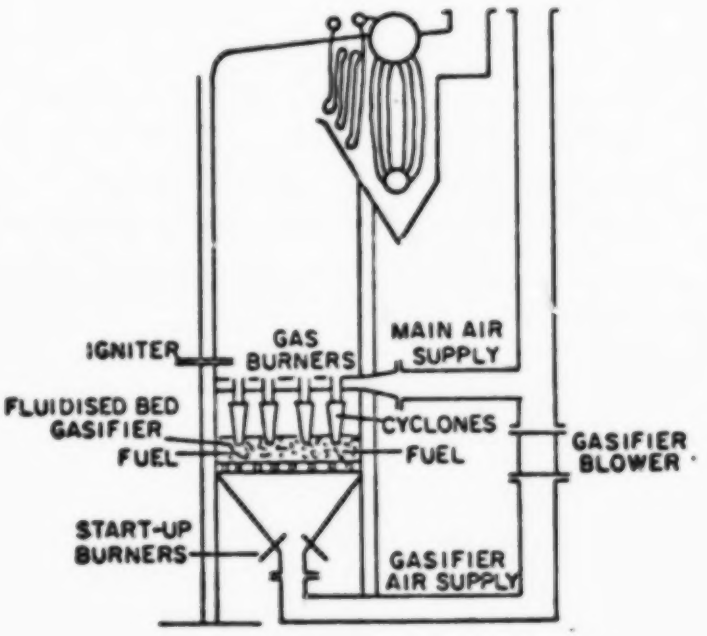


Fig. 12. Chemically Active Fluidized-bed Boiler Conversion (Esso Ltd. Research Centre[21])

A combined gas-turbine and steam-turbine cycle has also been proposed. This system, shown in Fig. 13, uses the fluidized-bed combustor not only as a compact boiler but also as a means for removal and subsequent recovery of both sulfur and vanadium from residual fuel oil. This scheme was proposed to Esso by Professor Elliot, who is currently a consultant to the NCB. Esso believes that this scheme also offers the possibility of concentrating the SO_2 produced during regeneration by dissolving it at the working pressure in a suitable solvent (possibly calcium bisulfite solution) and then stripping the solvent at atmospheric pressure.

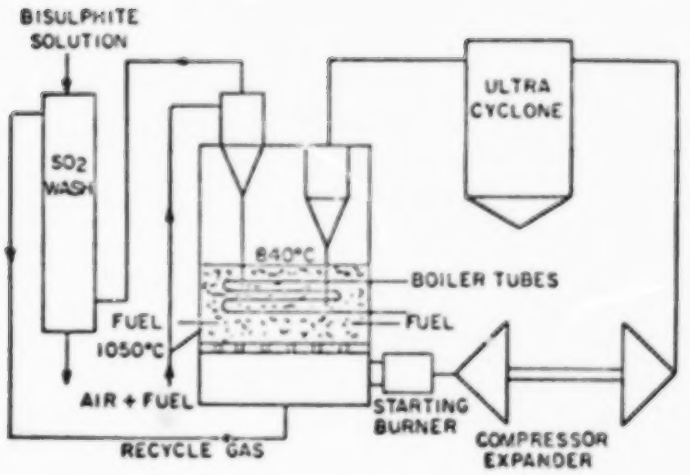


Fig. 13

Gas Turbine/Steam Cycle
(Esso Ltd. Research Centre[21])

VI. PLANNED EXPERIMENTAL WORK

A. Coal Research Establishment

The next stage of development at CRE will involve experimentation on a newly constructed 3-ft-square pilot-plant combustor. The unit has a mild-steel outer wall, a layer of refractory, and a stainless steel (EN58B) inner liner. Cooling tubes (2-in. Schedule 80, stainless steel) can be accommodated at different orientations, alternative fluidizing bases can be fitted, and the free-board height can be altered. The off-gases are passed through two cyclones (36- and 24-in. diameter) in series, with provision for recycle of the fines from the first cyclone back to the bed if desired. Fines are recycled by pneumatically injecting the fines from the cycle using an external dip-leg seal. Bed height is automatically controlled by a ratio controller monitoring the bed density and pressure drop, which activates a rotary valve on a bottom takeoff point. Coal is pneumatically injected into the unit at one feed point using a 1-in.-diam feed line at a linear velocity of 30-40 ft/sec. The ratio of coal to transport air is about 20 lb of coal to 1 lb of air. Thus, under the expected operating conditions of 2- to 4-ft/sec superficial velocity, 6% of the total combustion air is introduced via the coal feed line. Currently the air distributor consists of a perforated plate with a ceramic overlay, but it is planned to use a water-cooled bubble-cap gas distributor. The unit is started up by feeding a mixture of hot combustion gases (from an external auxiliary burner) into the unit, together with a stream of the desired starter-bed material. A schematic engineering flowsheet of this pilot-plant facility was obtained from CRE.

The initial experimental work will concentrate on a single coal (Babbington), crushed to minus 10 BSS mesh, at 800-850°C and velocities of 2-4 ft/sec. The aim is to obtain data on combustion efficiency, carbon monoxide content of the off-gas, carbon elutriation from bed, size distribution and carbon content of ash, and problems associated with possible uneven distribution of coal in the bed. The overhead gases will be analyzed, under conditions of 20% excess air to mildly reducing, to simulate conditions that might exist in an actual boiler from uneven feeding of coal. The above

information, as well as other information that may be obtained from further mixing studies (tentative plans call for construction of a 10-ft-diam cold unit to study mixing and coal-feeding problems), will be used to develop an empirical model that will describe the necessary control features of a full-scale plant. Some experimentation will be done on the separate combustion at 900°C of fines to simulate the concept of a separate carbon-burnup cell. The goal is to accumulate the above information by June 1969, to coincide with the expected completion of initial design studies.

After June 1969, emphasis will be placed on the testing of various distributor designs (low pressure drop, 6 in. water), determining the effect of varying the height of freeboard above bed on quantity and carbon content of elutriated material, heat-transfer tests, and some testing of alternative startup systems.

CRE is also constructing a new 1-ft-square unit for long-term (1000-hr) erosion, corrosion, and fouling tests. They plan to use an existing 1-ft-square unit for any supporting tests necessary for operation of the 3-ft-square pilot plant.

Preliminary testing has started on the pilot-plant unit. Briefly, the initial tests have indicated that the overall carbon monoxide levels in the off-gas were lower than the results obtained with the 6-in. unit. However, problems with coal and air distribution have resulted in local concentrations of carbon monoxide over portions of the bed (approximately 1 vol %, 1 ft above bed) that have resulted in temperatures 50-100°C higher than the bed temperature due to the combustion of CO above the bed. Steam injection was used to keep these temperatures down. An estimated 5% of the overall heat release occurred above the bed. The carbon associated with the elutriated material was slightly higher than noticed in earlier work, but again this could be related to the coal and air distribution.

Mention was made of apparently indefinite plans to start some studies of burning 1/8-in. coal at 6-8 ft/sec as an experimental backup for the Packaged Water-tube Boiler Program.

B. BCURA

1. Shell Boiler--8000 lb of Steam per Hour[23,24]

BCURA's principal experimental work associated with the development of shell boilers will be done using an experimental prototype, four-pass, vertical shell boiler, rated at 8000 lb of steam per hour. This unit is expected to be in operation in May 1969.

The fluid bed will be contained in a 4-ft-diam, 4-ft 5-in.-high mild-steel furnace. A schematic diagram of the equipment is shown in Fig. 14. The bed will be 2 ft deep and pierced by thirty $2\frac{1}{2}$-in.-OD tubes at an angle of 10° to the horizontal, allowing about 50% of the heat released to be extracted from the bed. The boiler will incorporate a fully enclosed, pneumatic coal-feeding system. Four separate coal-injection points will be used. The linear velocity used in the feed lines will be 100 ft/sec with about 4 lb of coal per pound of air. The off-gases from the unit will pass through two cyclones in series with provisions for recycle of captured material from the first cyclone back to the bed. It is expected that 50-60% of the material that is elutriated will be captured by the first cyclone and will be greater than 200 mesh. The overall height of the boiler will be $11\frac{1}{2}$ ft and the diameter, 8 ft. This is about half the overall size of an equivalent chain-grate Economic Boiler. The unit will burn 800-1000 lb/hr of a high-ash, minus-1/4-in. coal to produce an estimated $8\frac{1}{4}$ lb of steam per pound of coal. This represents a target of 80% thermal efficiency for a gas outlet temperature of 200°C and not more than 5% heat loss due to carbon in ash.

Among the purposes of the tests will be confirmation that the system is practical, safe, and reliable, is not unduly sensitive to fuel supply, is easy to maintain, is amenable to automation, has a satisfactory turndown ratio, and can be installed and operated at a competitive price.

The unit has a design capacity of 8000 lb of steam per hour at a velocity of 10 ft/sec. The upper limit is about 14 ft/sec (10,000 lb of steam per hour), and the lower limit, where part of the bed will start to go static, is about 7 ft/sec. Operating at the lower velocity and using 100% excess air will give an output of 2500 lb of steam per hour and an overall turndown of 4 to 1.

The existing 2-ft-diam fluidized-bed unit will be used to supply necessary support information for the experimental prototype as well as to investigate the combustion of minus-1/8-in. coal at velocities of 6-8 ft/sec to supply experimental data for the Packaged Water-tube Boiler concept.

2. Fluidized-bed Combustion under Pressure[23,25,26]

The main objective of the experimental work of BCURA on pressurized fluidized-bed combustion is to investigate whether the combustion gases from a fluidized bed can be sufficiently well cleaned to avoid undue erosion of gas-turbine blades, without incurring unacceptably high power or capital cost, and to determine whether volatilization of constituents of the mineral matter of the ash is low enough to avoid serious fouling or corrosion of turbine blades. In addition, information is needed on heat-transfer rates, combustion efficiency, coal distribution, and the effect of high tube-packing densities.

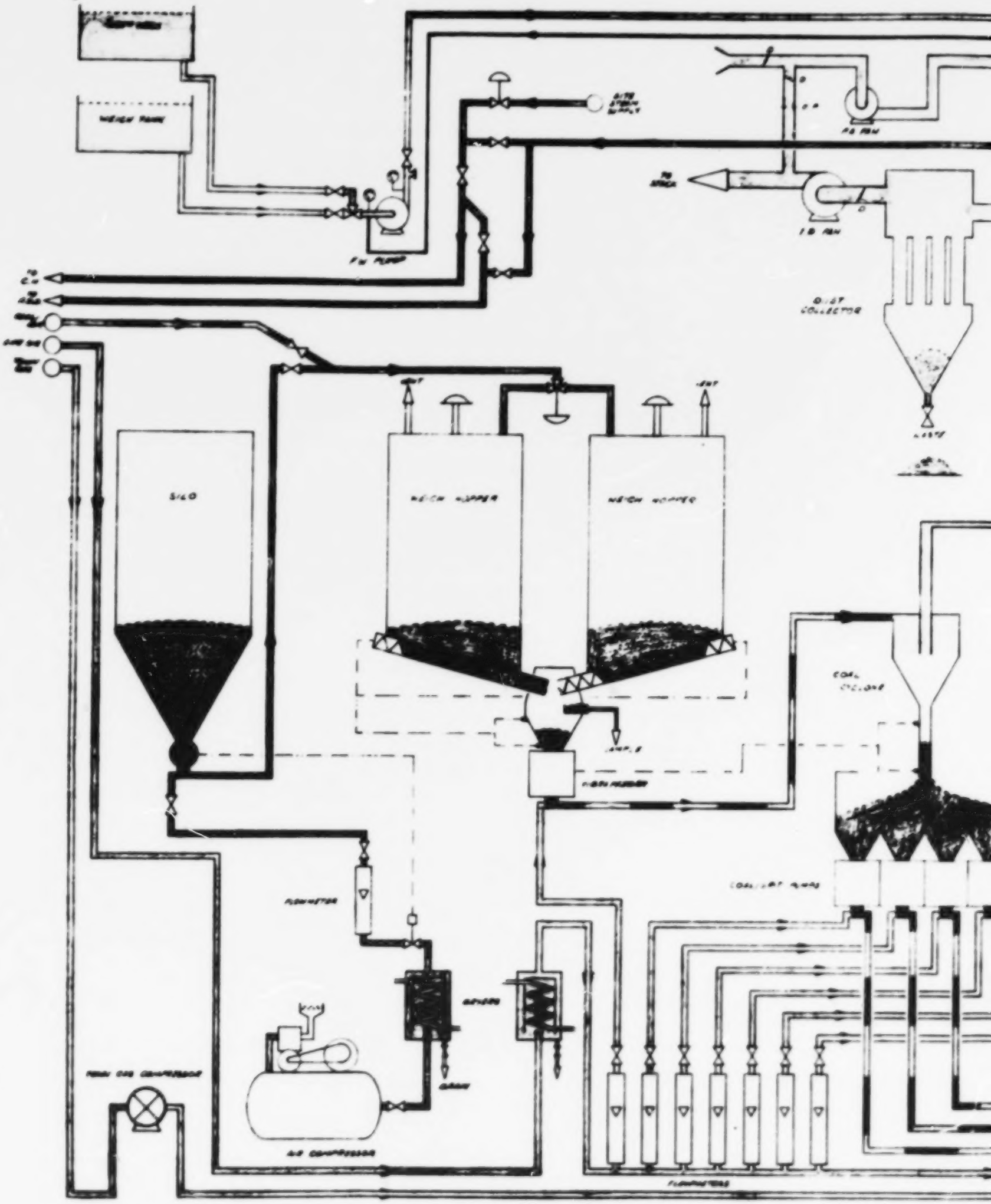
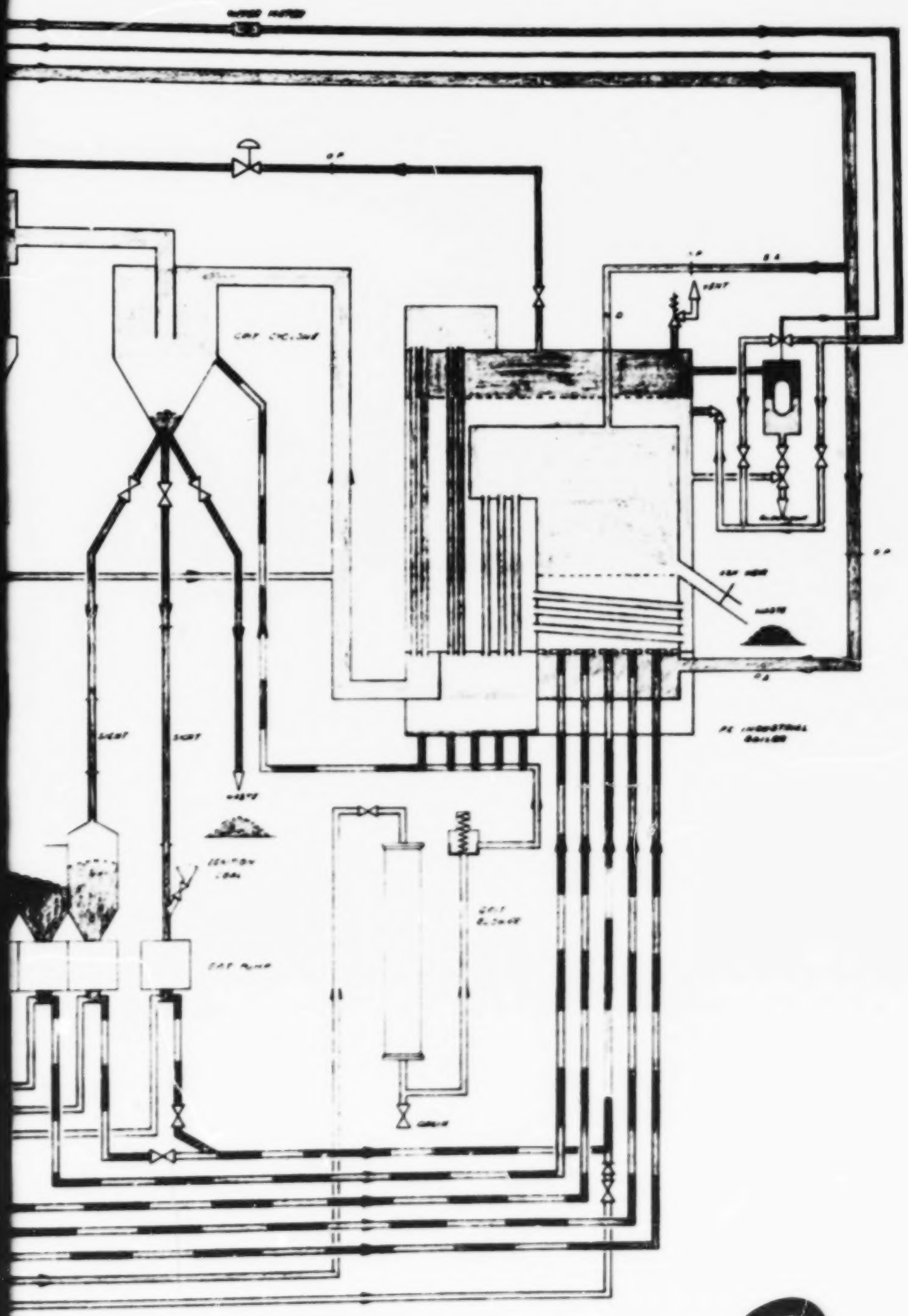


Fig. 14. Shell Boiler with Capacity of 8000 lb of Steam per



per Hour (BCURA Industrial Laboratories[24])

The main experimental equipment being fabricated for these investigations is a pilot-plant stainless steel combustor designed to burn 1000 lb/hr of minus-1/16-in. coal at 5 atm and 650-800°C. A schematic diagram of the equipment is shown in Fig. 15. The rectangular fuel bed is 4 ft long, 2 ft wide, and about $2\frac{1}{2}$ ft deep, and contains 1-in.-OD tubes spaced on 3-in. centers. These tubes will hopefully remove as much as 60% of the heat released during combustion and will also be used to preheat the combustion air. The entire unit will be placed within a 6-ft-diam pressure shell.

The superficial velocity used will depend (with a fixed heat-transfer area) on the heat-transfer coefficients obtained and the desired bed temperature, which will dictate the required heat input to the unit. Velocities in the range of 2-6 ft/sec will probably be used. Elutriated solids will be removed from the off-gas with a cyclone and returned to the fluid bed using an internal dip leg. After being cleaned, the gases will pass over a set of turbine blades mounted in cascade and over superheater tubes for information on erosion, corrosion, and deposition of material. It is also planned to incorporate, at a later date, a small gas turbine to permit more realistic testing of the system.

In addition to the main pilot-scale combustor, a full-scale model operating at atmospheric pressure and temperature is being built. This will be used to determine fluidizing conditions and to determine the rapidity of mixing of coal after injection into the bed. The unit will also be used to study methods of heating the bed for startup.

An erosion rig (2 x 2 x 2 ft) operating at atmospheric pressure is being built to measure the extent of abrasion of tubes immersed in the bed. The extent of erosion will be measured by surface profilometry using an instrument capable of measuring metal losses equivalent to 1 μm.

Laboratory-scale experiments will be carried out to study the release of alkali and sulfur from the coal and absorption on mineral-matter particles. Small fluidized beds will be used. The laboratory studies will be backed up by establishing sulfur and alkali balances on the pilot-scale unit.

VII. CONCEPTUAL DESIGN STUDIES

The following information on the conceptual designs of various units is based on discussions with personnel from CRE and BCURA. No direct access to the reports was obtained.

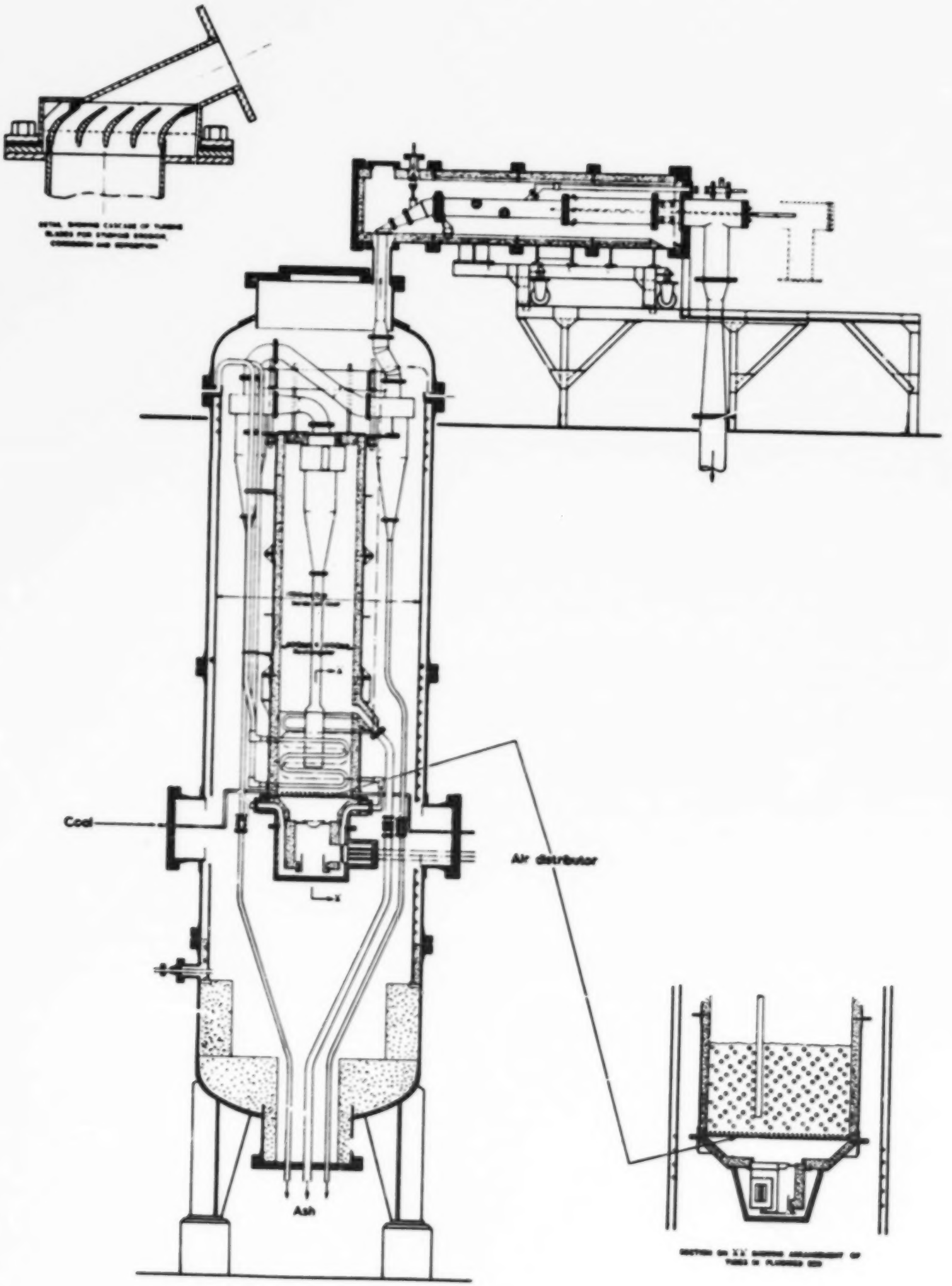


Fig. 15. Pressurized Fluidized-bed Boiler (BCURA Industrial Laboratories[25])

A. Babcock & Wilcox Ltd. 660-MW Design

The conceptual design study being done by Babcock & Wilcox (B&W) Ltd. for the NCB on a 660-MW fluidized-bed utility boiler has been under way for 5-6 months. Completion was hoped for in April 1969. The design is based for the most part on the data obtained by CRE. The concept involves the combustion of coal, crushed to minus 1/16 in., at a superficial fluidizing velocity of 2 ft/sec, in 2-ft-deep beds at 850°C and 20% excess air. These conditions were selected to ensure high heat-transfer rates (small particles) and to minimize elutriation of carbon-containing fines (low velocity) so that high overall carbon efficiencies could be achieved. The proposed boiler was designed with two vertical rows of eight beds each, with a plenum between the rows for the off-gases. Each bed will be 20 x 80 ft in cross section, and the overall height of the boiler about 100 ft. The overall volume is stated to be about half that of a pulverized-coal-fired unit. Hairpin tubes in each bed will absorb greater than 50% of the total heat released. After passage through the convective tubes on the walls and roof of each bed chamber, which will pick up 5-10% of the heat released, the off-gas will be cooled from 850 to 750°C and pass into a separate economizer. The economizer is designed to cool the exit gas to 350°C and to absorb approximately one-third of the total heat released. After passage through the economizer, the dust-laden gases will be passed through cyclones and spinners to capture carbon-containing fines, which will be fed to a separate carbon-burnup bed at the base of the boiler. The area of this bed is about double that of one of the other beds. It will be run at about 900°C and about half the velocity of a primary bed.

The coal-feeding system is similar to that used to feed blast furnaces. A pressurized-lock hopper system will be used with six lines exiting from each hopper. These lines are each subsequently split four times, giving 24 main feed points per hopper. The uniformity of feed from each line is expected to be 5-10%. The feed will be pneumatically injected at about 20 lb of coal per pound of transport air. Tentative plans call for one feed point for each 100 ft^2 of bed area, which would require 256 feed points for the 16 beds. This is believed to be optimistic and a principal area of experimental study.

The solids-recycle requirements of the system call for a bleed-off of 5% of the solids collected by the cyclones. This would make the quantity of recycled material approximately equivalent to the coal feed rate, and allow sufficient residence time of the solids in the system to ensure carbon burnup and high overall combustion efficiency. If additional residence time were required and larger recycle rates were necessary, the heat associated with the dust particles would be a significant load on the economizer. In other words, since the quantity of heat leaving the boiler proper is increased, the amount available for pickup by the tubes immersed in the bed would be

decreased, and some of the advantages of fluidized-bed combustion would be diminished. This could be overcome if the solids were separated from the gas before passage through the economizer and hot solids were recycled to the bed, but only at the expense of higher costs for cyclones capable of handling the higher-temperature gases.

Accumulated ash will be removed from each bed by the overflow method.

Without any beds being taken out of service, a turndown to 70% of normal output can be achieved by decreasing the coal and air input.

The above design was selected by B&W over an initial concept proposed by the NCB,[27] which was a more radical departure from a conventional unit. The earlier concept involved 10 units, each 20 ft wide and 100 ft long, arranged horizontally with the ductwork manifolded to a common exhaust. One advantage of this design was said to be a reduction in structural steelwork and massive foundations. The NCB is still considering alternative designs to the current B&W concept. In particular, the suitability of a once-through steam system is being considered, which may be more suitable to a horizontal design. A once-through system would require forced convection, and there would be no need for a boiler drum.

The intention to obtain several alternative conceptual designs was mentioned. It was suggested that a conceptual design might be obtained from a firm knowledgeable in nuclear-powered electrical generating systems in the hope of avoiding the inertia to change of manufacturers of conventional coal-fired boilers.

B. John Thompson Ltd. Shell Boiler

The conceptual design of the shell boiler is typified by the 8000-lb of steam per hour experimental prototype being constructed at BCURA and described in Section VI.B.1 above.

The largest shell boiler envisioned is about 50,000 lb of steam per hour, which might be constructed as two fluidized-bed combustors contained in a single shell. The presently envisioned maximum diameter of such a shell would be 12 ft. Two 4-ft-diam fluidized-bed units might be contained within the shell. The diameter of the fluidized-bed units is limited by the temperature drop across the fluidized-bed walls and the water shell and an overall steam-pressure rating of about 200 psi.

C. Preece, Cardew, and Rider Ltd. Packaged Water-tube Boiler

The NCB has a contract with Preece, Cardew, and Rider (P, C, and R) Ltd., a consulting engineering firm, to work out a conceptual design

study for a 120,000 lb of steam per hour packaged water-tube boiler. The firm has selected 8 ft/sec as the fluidizing velocity and coal crushed to minus 1/8 in. This was a trade-off between high heat-release rates, which require high velocity, and low carbon loss, which requires low velocity. The materials of construction of the tubes for the unit are mild steel, except for the superheater tubes, which are stainless steel. A preliminary costing of such a unit indicates that it would be economically attractive, and P, C, and R recommends that an experimental prototype be built. Approximately 14-20 units of the 50,000-120,000 lb of steam per hour size are built in England each year. The cost study indicated an economic edge for a coal-fired, fluidized-bed unit, unless the price of gas falls to 4.2 pence/therm (lowest gas price likely, 5.0 pence/therm). The price of fuel oil is currently 6.84 pence/therm.

VIII. COST ANALYSES

The Research and Development Department of the NCB has done a preliminary cost analysis of utility-sized fluidized-bed systems compared with conventional pulverized-fuel-fired stations. Included in the study were the comparative effects of installing a dry limestone injection process to reduce the emission of SO_2.

The analysis was based on the assumption of a 50% reduction in the SO_2 level of the flue gas and requirements of one stoichiometric quantity of CaO for a fluidized-bed system and twice the stoichiometric quantity of CaO for a conventional system. The results are shown in Table III for coals of various sulfur contents.[28]

TABLE III. Cost of Removal of 50% of SO_2 ($/ton of coal) for Conventional Pulverized-coal Units and Fluidized-bed Combuction Systems (National Coal Board, Research and Development Department[28])

Sulfur in Coal, %:	1.0	1.5	2.0	2.5	3.0	3.5
Pulverized-coal fired	0.26	0.38	0.51	0.62	0.73	0.84
Fluidized bed	0.16	0.24	0.30	0.37	0.44	0.52

It was stated that the capital charges for a pulverized-fuel-fired unit in 1975 would be £55/kW ($132/kW), compared with £50/kW ($120/kW) for a fluidized-bed unit. If limestone injection were included for both systems, the charges would be £57/kW ($137/kW) for a conventional system and £52/kW ($125/kW) for a fluidized-bed unit. Hence, the cost of SO_2 removal is expected to be less than the expected savings in going from pulverized-fuel-firing to fluidized-bed systems.[28]

The Research and Development Department personnel have also done cost studies on the feasibility of increasing steam temperatures, which may be possible with a fluidized-bed unit because of the reduction in corrosive constituents in the gas contacting the steam tubes. They believed that the temperature of the steam cycle could be pushed to 600°C without drastically redesigning steam turbines, and that the resultant overall gain in cycle efficiency would more than offset the cost of higher-strength materials for the tubes.

IX. COMMENTS AND DISCUSSION

The development program on fluidized-bed combustion being pursued by the NCB appears to be a sound, well-planned, well-directed effort. The experimental studies at CRE and BCURA are comprehensive and are being carried out by capable personnel. However, the program is on a very tight timetable since the goal is to provide a commercial version of fluidized-bed coal combustion before nuclear energy becomes too firmly entrenched as a power-generating source. Therefore efforts are aimed chiefly at providing technical data for most conceivable problem areas rather than toward optimization.

A. Major Problem Areas

Three major problem areas must be resolved for the successful application of fluidized-bed combustion. These areas are: coal distribution, air distribution, and recycling of elutriated fines.

1. Coal Distribution

The required spacing of coal feed points for a large-sized fluidized-bed combustor has not been firmly established. This is a particularly important point, since, if feed points are too far apart, the available oxygen in the vicinity of the feed point will be consumed, resulting in possible release and burning of carbon monoxide above the bed. This would decrease the heat available for pickup at high rates by the tubes immersed within the bed itself. In addition, this condition is undesirable because of local high temperatures above the bed and possible local reducing conditions within the bed itself. Both of these effects could cause corrosion problems.

Coal distribution is not necessarily related only to the minimum number of feed points per reactor cross-sectional area. The release of carbon monoxide above the bed depends also on bed depth and gas velocity; although little carbon monoxide has been noted above 2-ft-deep beds over the velocity range of 2-14 ft/sec in smaller experimental units, information is needed from larger units. Heat release above the bed was noted at high

velocities and low bed depths during early work at BCURA and has also been noted in the preliminary runs of the 3-ft-square pilot-plant rig at CRE.

NCB personnel have stated that the 660-MW design concept of one feed point per 100 ft^2 of reactor cross-sectional area appears to be optimistic, and they plan to do further work on coal distribution in the 3-ft-square pilot-plant unit as well as, tentatively, in a 10-ft-diam cold unit. BCURA is also studying the advantages of variously shaped end pieces for the coal-distribution line.

The coal-feeding system for the 660-MW concept does not use individual metering of the flow at each feed point. It involves six main feed lines from each hopper, which are each subsequently split four times. The variation in flow from each line is expected to be only 5-10%. This concept needs to be demonstrated, since it appears to be optimistic.

2. Air Distribution

The need for efficient distribution of air across large-diameter fluidized beds is related to the efficient contacting of coal and air to minimize (1) bypassing of air and (2) the formation of carbon monoxide in local areas of the bed. Although large-sized industrial fluidized-bed chemical-processing units are in operation, this problem is compounded for a fluidized-bed coal combustor because the distributor must be of a low-pressure-drop design to minimize fan costs. The NCB is pursuing this problem in discussions with industrial concerns on the design of gas distributors and plans to test a water-cooled bubble-cap-type distributor in the pilot-plant rig.

Previous results with experimental equipment have shown satisfactory overall levels of CO in the flue gas, although the concentration has increased with decreasing distance above the bed surface. In general, the amount of excess air required to achieve satisfactory overall levels of carbon monoxide in the flue gas would be expected to increase with larger units, where air distribution is poorer. Results of tests with the 6-in.-diam unit indicated low overall CO levels with as little as 5% excess air, whereas the design concepts involve 20% excess air.

3. Recycle of Elutriated Fines

The principal carbon loss from a fluidized bed is due to the carbon content of fines that are elutriated from the bed. To achieve satisfactory overall carbon efficiencies for a fluidized-bed combustor, a large fraction of these fines must be recycled to the fluidized bed or to a separate fly-ash burnup cell. The quantity of carbon lost from the system without recycle depends upon the particle size of the coal and the superficial gas

velocity. With recycle, it depends also upon the number of times a carbon-containing particle is cycled through the system before it is finally discharged. This latter fact, as well as the fly-ash content of the coal, determines the dust loading of the gas stream, the cyclone requirements, and the required mass rate of recycle.

Two alternative recycle modes exist. One concept calls for recycle of all material collected by a primary cyclone, which permits the very fine particles to leave the system. The other concept uses a very efficient cyclone and bleeds off a portion of the total size range before returning the remaining solids to the fluidized-bed unit. The mode of operation selected depends upon the desired carbon efficiency and the carbon content of the various size fractions of fly ash. The shell-boiler design of BCURA uses total recycle of all fines captured by a cyclone designed to retain particles greater than 75 μm. The 660-MW utility-boiler concept provides for a cyclone that captures all fines greater than 10 μm and bleeds off a portion of this material before recycle to a carbon-burnup cell. Calculations indicate that a bleed-off rate equivalent to 5% of the material collected by the cyclone would lower the recycle requirements to about that of the coal feed rate, i.e., 10 lb/hr per square foot of bed cross section.

The quantity of material that has to be recycled can affect the economics of fluidized-bed combustion. If the solids-laden gas stream is not cooled before passage through cyclone separators, then the materials of construction requirements and the size requirements of the cyclones make this equipment relatively expensive. If the solids-containing gas stream is passed through heat-recovery equipment such as an economizer before passage through the cyclones, then the heat load on the economizer may become large due to the heat capacity of the solids in the gas stream. Heat absorbed by the economizer is a portion of the total heat released during combustion that is unavailable for pickup by the tubes in the fluidized bed.

British coals have higher ash contents than most U.S. coals. However, tests on one U.S. coal at CRE indicated that although the total ash content was lower, all the associated ash was elutriated during combustion. Experimental data on U.S. coals to determine the elutriation characteristics of the ash and recycle requirements to achieve desired overall combustion efficiency are lacking.

The recycle problem may be compounded if an additive such as limestone is introduced to the system to control pollution. Decrepitation of additive material would add to the overall quantity of material that has to be recycled. The concept of recycling all elutriated material to a separate cell for burnup of carbon may not provide the same degree of SO_2 removal that would be achieved if recycle to individual combustor cells were provided. More information is needed to evaluate the importance of these factors.

The means of feeding very fine material from the cyclone separators back to a fluidized-bed cell will require additional investigation because of the physical differences in the character of these solids compared with the coal feed. In addition, information is needed to determine if the required solids residence time and recycle rates could be lowered by the combustion of these fines at higher temperatures and lower velocities in a fly-ash burnup cell.

Achievement of the required overall carbon efficiences has not yet been demonstrated for the shell-boiler concept. Calculations indicate that if all material of a particular size were recycled, 95% efficiency would be achieved. Confirmation of this efficiency is one of the prime goals of the BCURA experimental program with the new 8000 lb of steam per hour experimental prototype.

Acceptable carbon efficiencies for the 660-MW utility boiler concept have been demonstrated at CRE only in a 6-in.-diam unit where the residence time of elutriated particles in a hot zone may not be typical of that expected for a full-sized boiler. A current goal of the CRE experimental program with the 3-ft-square pilot plant is to provide data on the overall combustion efficiency under conditions more typical of a large-scale unit.

B. Other Areas Requiring Study

In addition to the above problem areas, other facets of fluidized-bed combustion need further study.

1. Bed Stability

Additional investigation is needed on the long-term stable operation of a fluidized-bed combustor. The heat-transfer coefficient for tubes immersed within the bed depends upon the particle size of the bed material. The combustion of various coals results in substantial size differences of the resultant ash. Information is needed on the sensitivity of fluidized-bed combustor characteristics (in particular the heat-transfer coefficient) to particle size differences of the fluidized bed resulting from normal variations within a type of coal or from changing the type of coal feed. Although various British coals have been tested, the character of the ash seems quite different from U.S. coals, as evidenced by the CRE tests of one U.S. (Farmington) coal and results obtained by Pope, Evans and Robbins in the U.S. The British feel that any change in average particle size of the fluidized bed would be slow and could be compensated for by adding a small amount of properly sized inert material with the coal feed.

Although there has been no evidence of sintering or clinkering problems with the coals tested, a typical cross section of coals that might

be expected to be used in the U.S. should be further examined. Methods for removing clinkers and tramp materials might have to be included in the design.

2. Startup

Although various schemes for startup of small experimental units have been used, satisfactory methods and data for the startup of larger units require further work. Schemes suitable for small experimental units may not be applicable where the bed is filled with cold-water-filled tubes.

3. Turndown

The British industrial-sized, fluidized-bed boilers are expected to have a turndown ratio or reduction in heat output of 4/1. This will be accomplished by reducing the fluidizing velocity from 14 to 7 ft/sec and operating with 100% excess air. At this reduced velocity, the lower part of the bed becomes static, and particles segregate. Extended operation at these lower outputs needs to be examined to see if operational problems occur. The turndown of the conceptual 660-MW utility unit to 70% of its rated output is accomplished by a reduction in fuel and air supply. Further turndown is accomplished by taking beds out of service. Additional details on the suitability of this technique need to be examined. There may be potential problems due to temporary increases in steam temperature during load changes.

4. Erosion, Corrosion, and Fouling

Long-term testing of the erosion, corrosion, and fouling of tubes and surfaces of a fluidized-bed combustor is needed to verify the lower rates expected for a fluidized-bed unit. This is particularly true for the pressurized fluidized-bed concept. Erosion of the roofs of the beds associated with the 660-MW design may also be a problem. A portion of the NCB program is involved with this type of testing. Information is needed, however, on the effect of a wide range of coals, with respect to differences in physical characteristics of the ash and the nature of the deposit formation.

5. Optimization of Operating Variables

Although it has been decided that smaller particle sizes and lower gas velocities are desirable for the design of large-scale utility fluidized-bed systems to achieve high heat-transfer coefficients and high carbon efficiencies, it has been agreed that the selected conditions may not necessarily be optimum. The B&W conceptual study indicated that the

cost of a utility-sized boiler is relatively insensitive to overall size, and hence no great economic incentive exists to go from 2 to 4 ft/sec, since this would increase the bed depth (at a fixed tube-packing density) and result in greater fan costs. Opinions on the soundness of this reasoning vary.

A comprehensive study appears to be needed of the interrelated effects of the variables coal-particle size (possibly including pulverized coal), gas velocity, and bed depth, on overall combustion efficiency, recycle requirements, boiler size, and cost. This may require additional information on the kinetics of coal combustion in fluidized beds, as well as additional data on the effects of size and arrangement of immersed tubes on combustion and the rate of heat transfer in the fluidized bed. The feasibility of using two stages of fluidized beds might also need investigation, since this concept could allow substantial further reduction in heat-transfer-tube requirements.

One criterion that B&W used for selecting the conceptual design was to retain as much as possible of conventional boiler concepts. It might be advantageous to have a company not associated with conventional coal-fired boilers attempt to design a unit that would more fully explcit the potential advantages of fluidized-bed combustion.

6. Safety Hazards

A study should be made of potential safety hazards peculiar to the operation of a fluidized-bed unit--in particular, the reaction of carbon within the bed with steam from a ruptured boiler tube, or a malfunction of either the fuel feed or combustion air supply, giving rise to a fuel-rich mix, which would release unburned gases from the bed. British opinion is that because of the low, steady-state carbon content of the bed, the system does not appear to offer unusual safety hazards, but a comprehensive analysis has not been made.

7. Potential for Pollution Control

Preliminary work by CRE and others has indicated that a fluidized-bed combustor has significant potential as a means of controlling the emissions of SO_2. A more thorough study should be made of the effects of different limestones, which are known to vary considerably in their reactivity, as well as of different coals, since the degree of SO_2 removal varied with different coals. In addition, the effects of additive particle size, gas velocity, bed depth, and other parameters must be analyzed to apply SO_2 pollution control to the different operating conditions of various boiler concepts.

Knowledge of the decrepitation of additive material must be obtained to evaluate a potential increased recycle burden and applicability of designs using a fly-ash burnup cell.

Further data on the amount of SO_3 formed during fluidized-bed combustion should be obtained. It was mentioned that lower amounts of SO_3 may enable the discharge temperatures of the flue gases to be lowered, which would effect higher overall steam-cycle efficiency. Data on SO_3 formation for the pressurized unit should be obtained, since the equilibrium for the SO_2-SO_3 reaction would favor more SO_3 formation at higher pressures.

The use of an additive for SO_2 control increases the quantity of ash that must be disposed of if a single-use system is employed. The economics of SO_2 control would be improved if a use for the spent additive were found or if a regenerable system were developed that recovered some sulfur value as well.

Work at Esso Research Ltd. on the combustion or gasification of fuel oil in fluidized beds of limestone and the subsequent regeneration of the spent limestone is of interest because of potential applicability to coal combustion. A similar mode of operation for fluidized-bed combustion of coal might be achieved by using a coal of very low ash content or by burning fine coal in a bed of relatively coarse limestone. Elutriation of virtually all the fly ash would be hoped for, along with little decrepitation of the limestone, in order to have a bed material that might be suitable for regeneration.

The potential for decreasing emissions of nitrogen oxides occurring during fluidized-bed combustion should be pursued. The work at BCURA has indicated that the nitrogen in the fuel could potentially contribute a part of the NO_x emissions, and has also indicated the possibility of using nitrogenous additives to reduce emissions.

8. Market Study

The market for industrial boilers (both shell and water tube) in the U.S. needs to be studied to determine the extent of potential interest in these types of fluidized-bed combustors. The study should take into account the potential of fluidized combustion for reducing capital costs and space requirements for both coal and oil fuels. Prospects for future availability of improved fuels, such as low-ash, low-sulfur coals, for such applications should be considered.

Knowledge of the contribution of industrial boilers to the air-pollution problem is needed to ascertain whether the industrial boiler concepts should be pursued because of pollution-control needs or for greater economy or merely to augment a program geared toward utility-sized, fluidized-bed units.

APPENDIX

List of Personnel Contacted

National Coal Board Headquarters (Hobert House, Grosvenor Place, S.W. 1., London)

Dr. A. M. Roberts, Director General of R&D Department
Mr. T. C. L. Nichole, Director of Administration, Research and Development Department (Coal Processing and Combustion)

Coal Research Establishment, National Coal Board (Stoke Orchard, Cheltenham)

Dr. J. Gibson, Director
Dr. A. D. Dainton, Deputy Director (Research)
Mr. J. McLaren, Head, Fluidized Combustion Section
Dr. D. F. Williams
Mr. M. J. Cooke
Mr. J. Highley
Mr. D. F. Stockwell

BCURA Industrial Laboratories (Leatherhead, Surrey)

Dr. L. C. F. Blackman, Director General
Mr. H. R. Hoy
Mr. G. G. Thurlow
Dr. S. J. Wright
Dr. J. T. Shaw
Mr. A. G. Roberts
Mr. J. A. C. Samms

National Coal Board, Research and Development Department (Harrow, Middlesex)

Mr. D. Gold, Head Project Assessment Branch
Mr. M. B. Bolt
Mr. J. S. Harrison
Mr. P. R. Sanderson

The following personnel were also present at some of the meetings:

Mr. F. Ireland, H. M. Chief Alkali Inspector
Prof. D. E. Elliot, University of Aston, Birmingham, consultant with the NCB

Esso Research Ltd., (Abingdon, Berkshire)

Dr. Peter J. Agius, Director of Research
Mr. Kenneth F. Ridley, Manager of Fuels Research
Dr. Graham L. Johnes, Section Head, Fuels Application
Dr. Gerry Moss, Fluid Bed Combustion

At the conclusion of the trip, a final meeting was held between P. W. Spaite of NAPCA and personnel of the NCB. Included among the attendees were:

Lord Robens, Chairman of the National Coal Board
Mr. Leslie Grainger, National Coal Board Member for Science

Both of the above report directly to the Minister of Power, who oversees the National Coal Board and the Central Electricity Generating Board.

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